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(54) **LINEAR FRESNEL SOLAR ARRAYS**

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See application file for complete search history.

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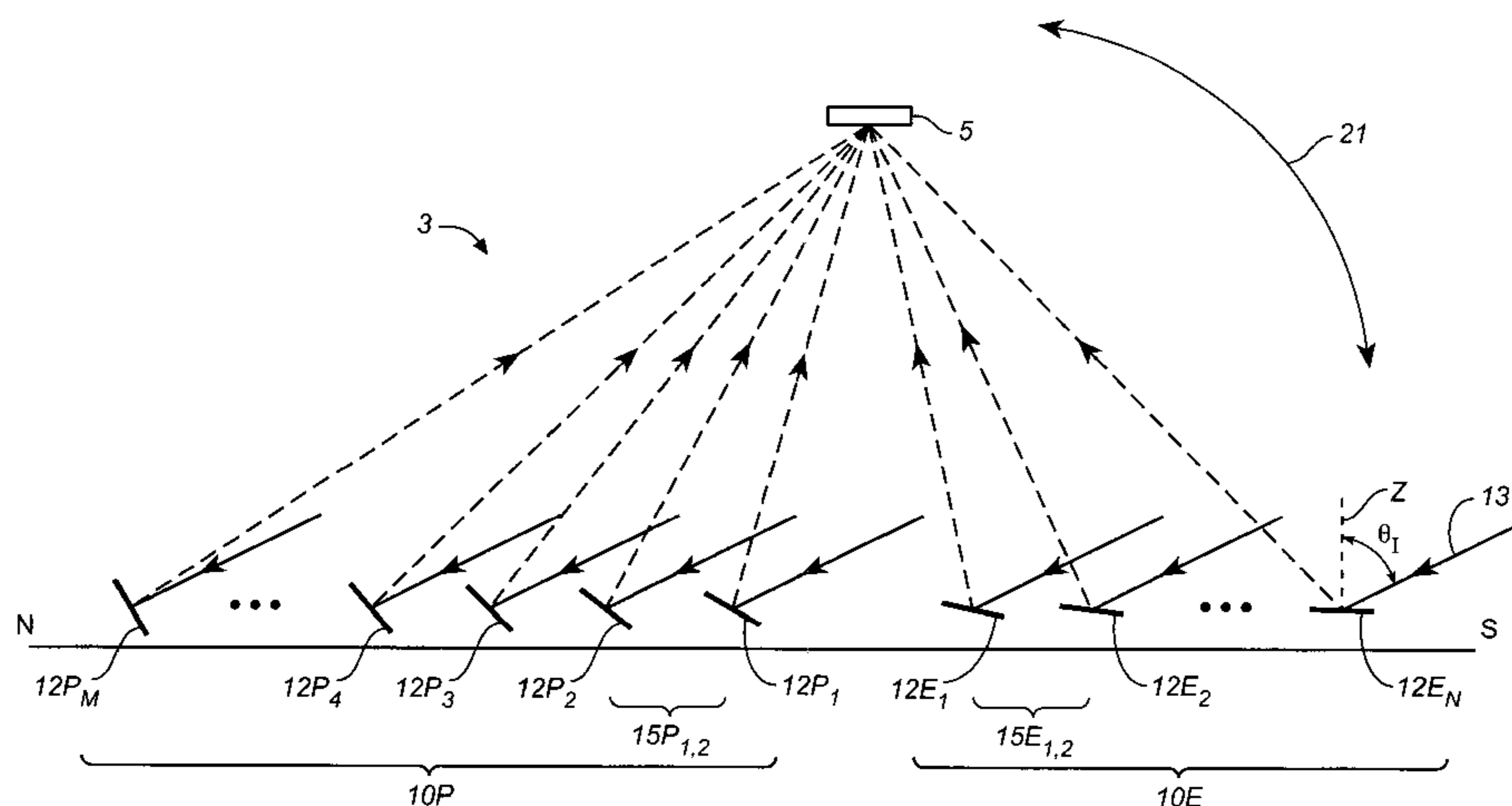
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(57) **ABSTRACT**

Disclosed herein are examples and variations of solar energy collector system comprising an elevated linear receiver (5) and first and second reflector fields (10P, 10E) located on opposite sides of, and arranged and driven to reflect solar radiation to, the receiver (5). Also disclosed herein are examples and variations of receivers (5) and reflectors (12a) that may, in some variations, be utilized in the disclosed solar energy collector systems.

**8 Claims, 15 Drawing Sheets**



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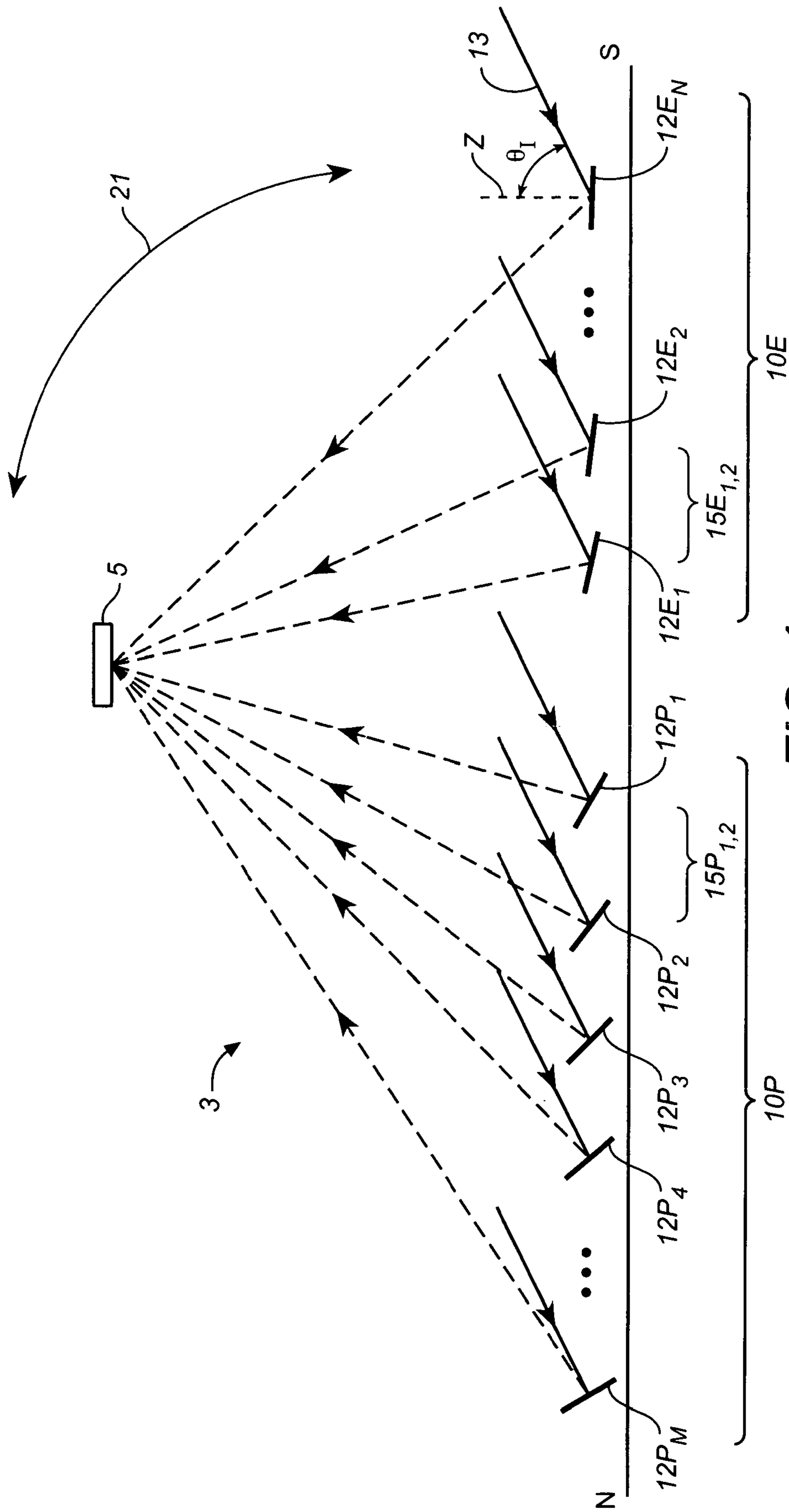
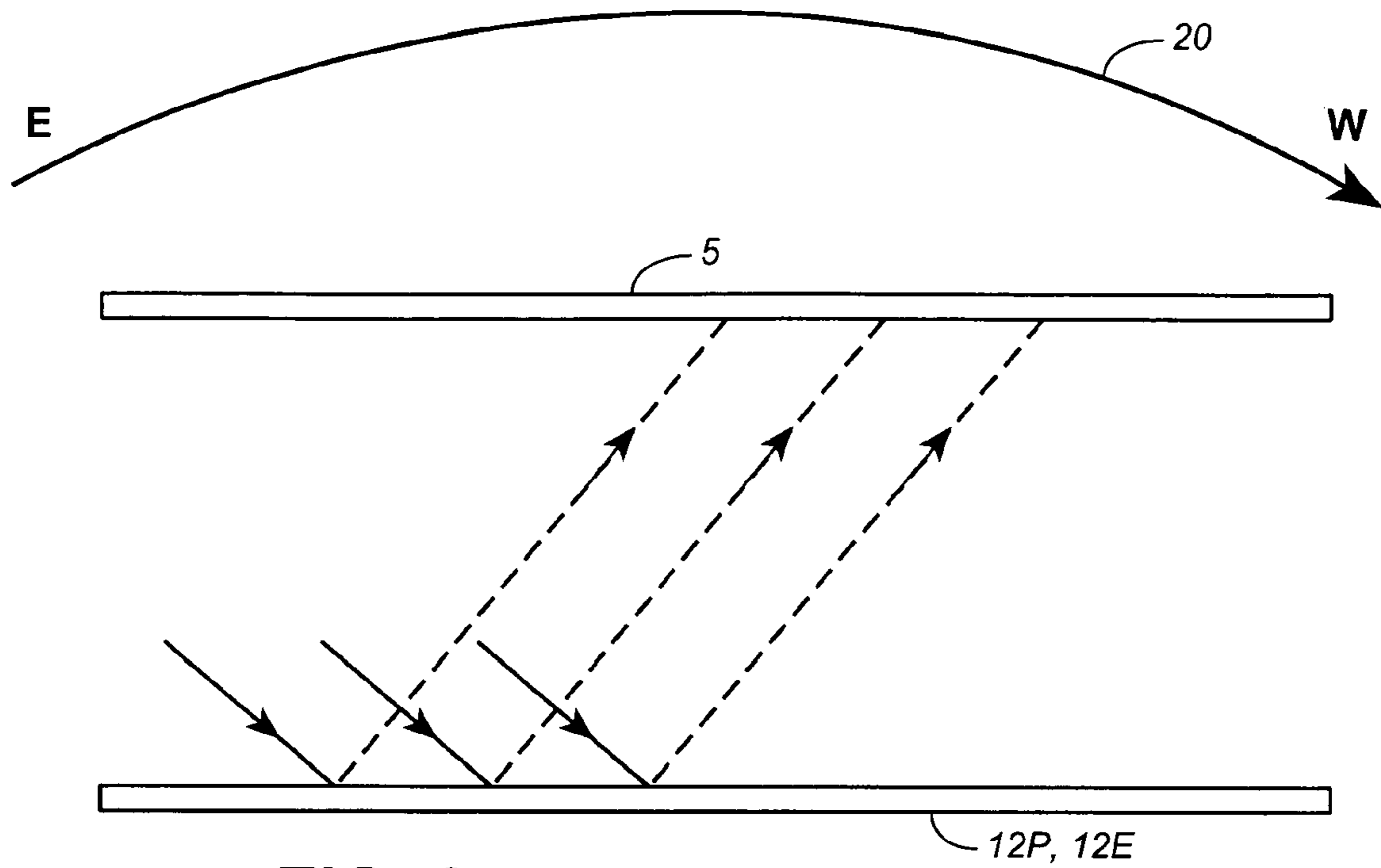
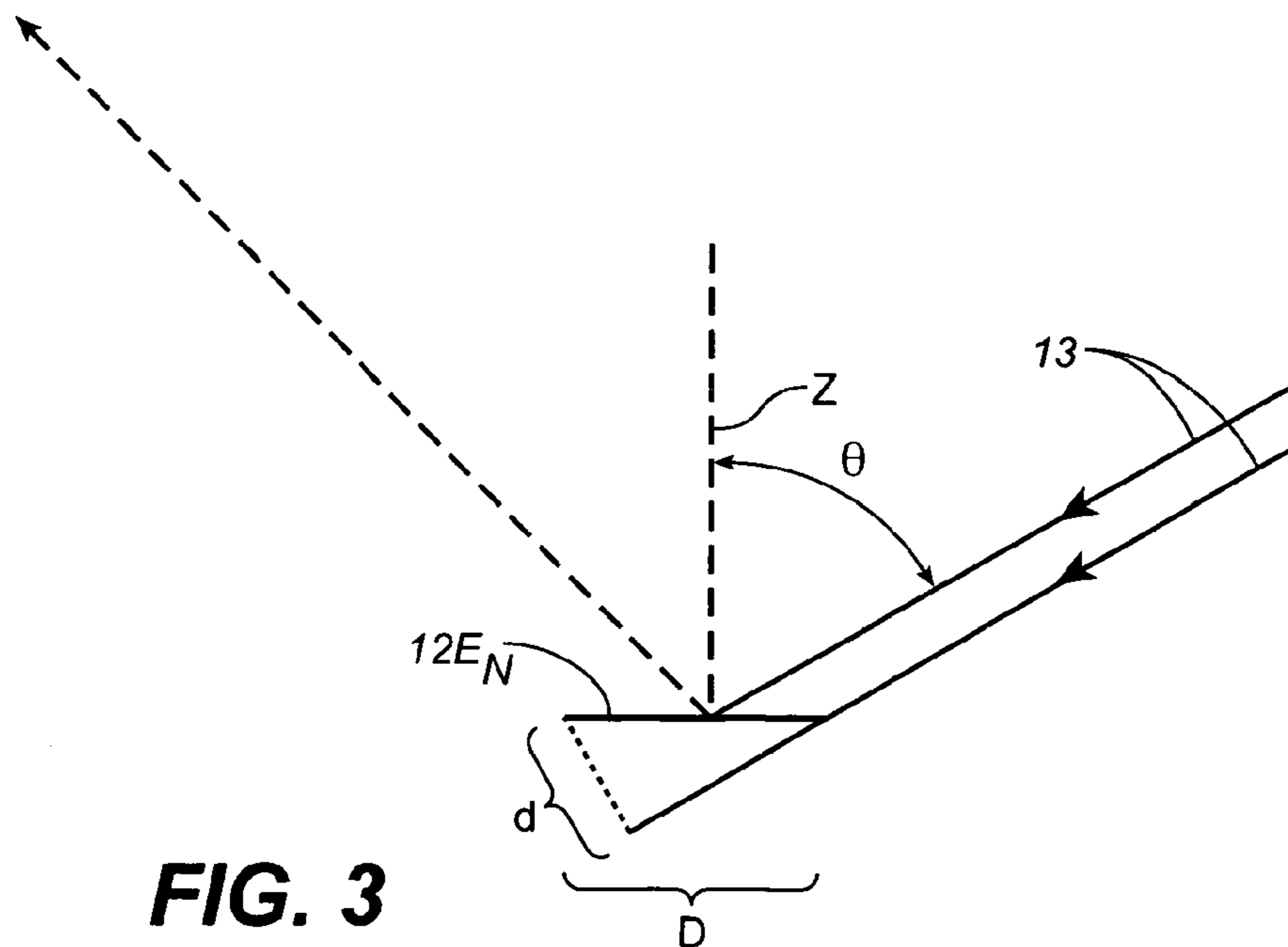


FIG. 1



**FIG. 2**



**FIG. 3**

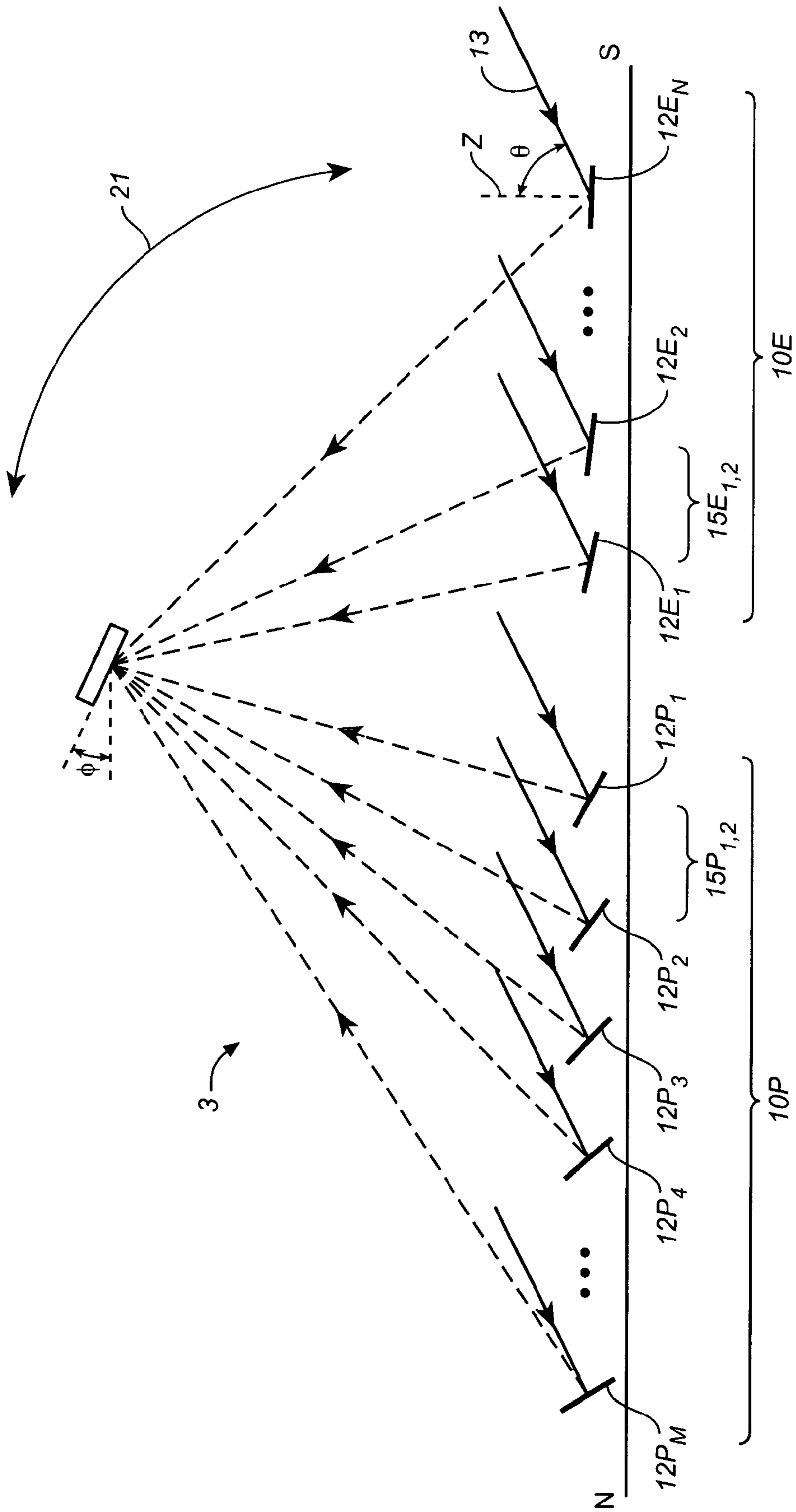


FIG. 4

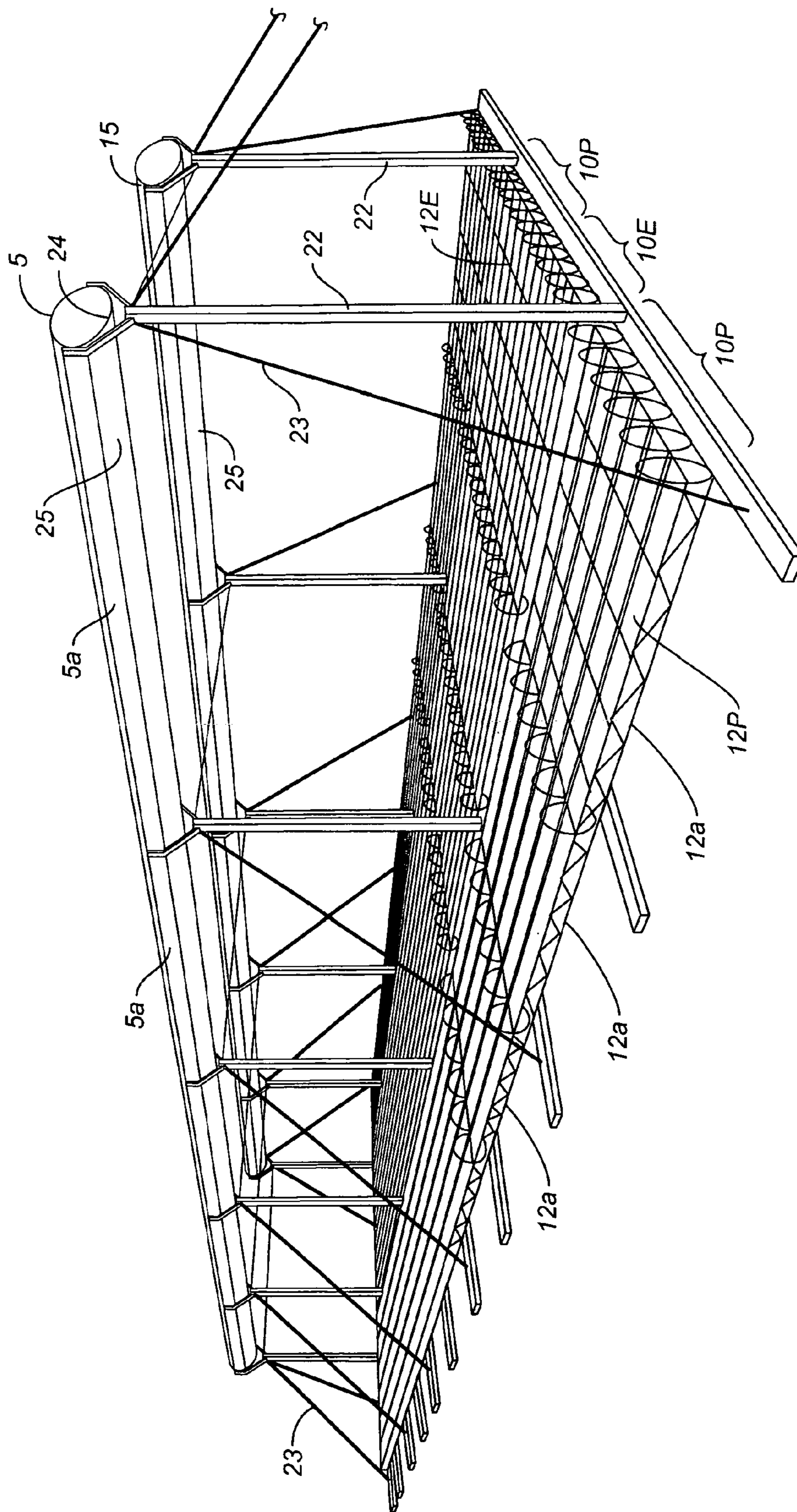
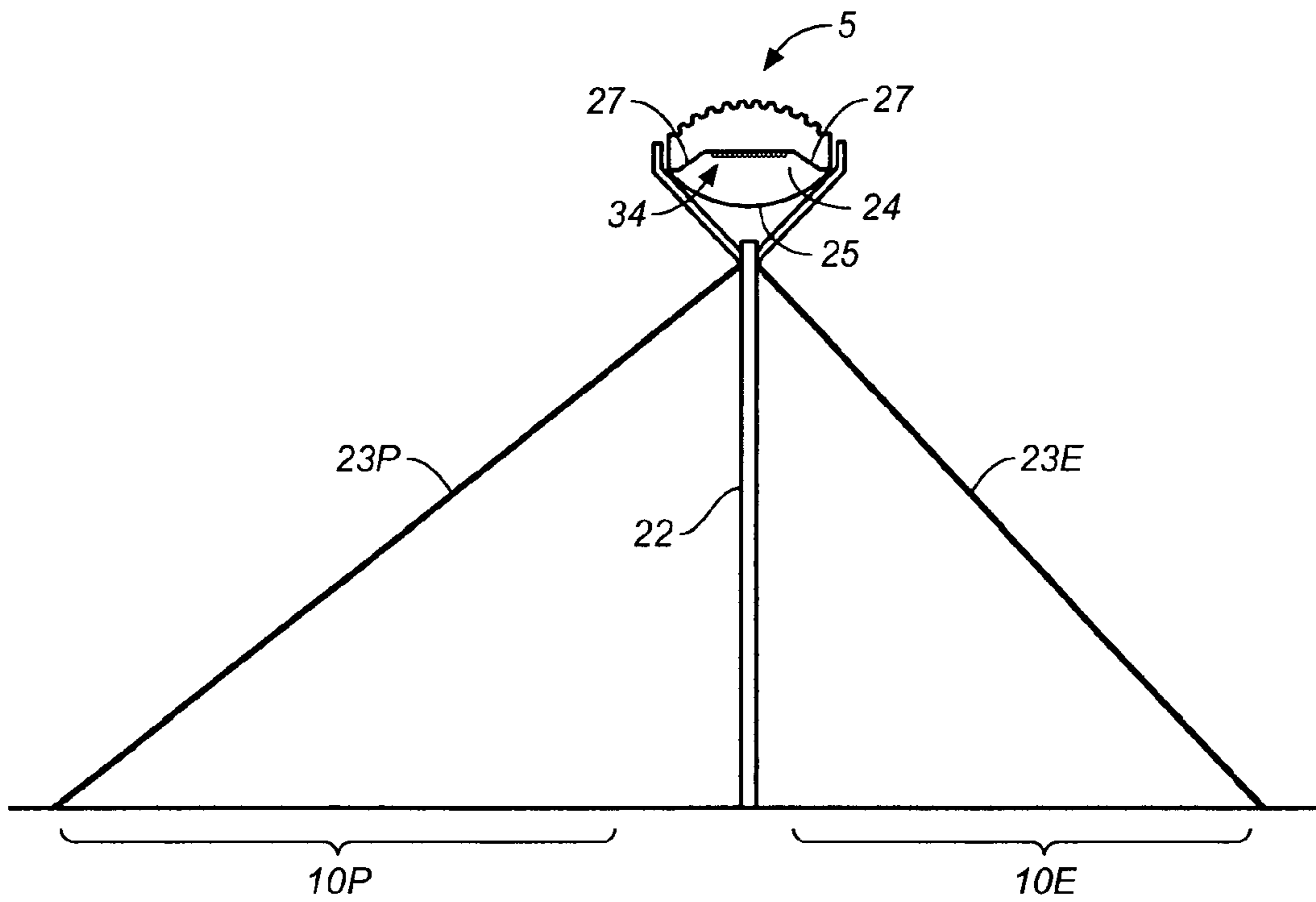
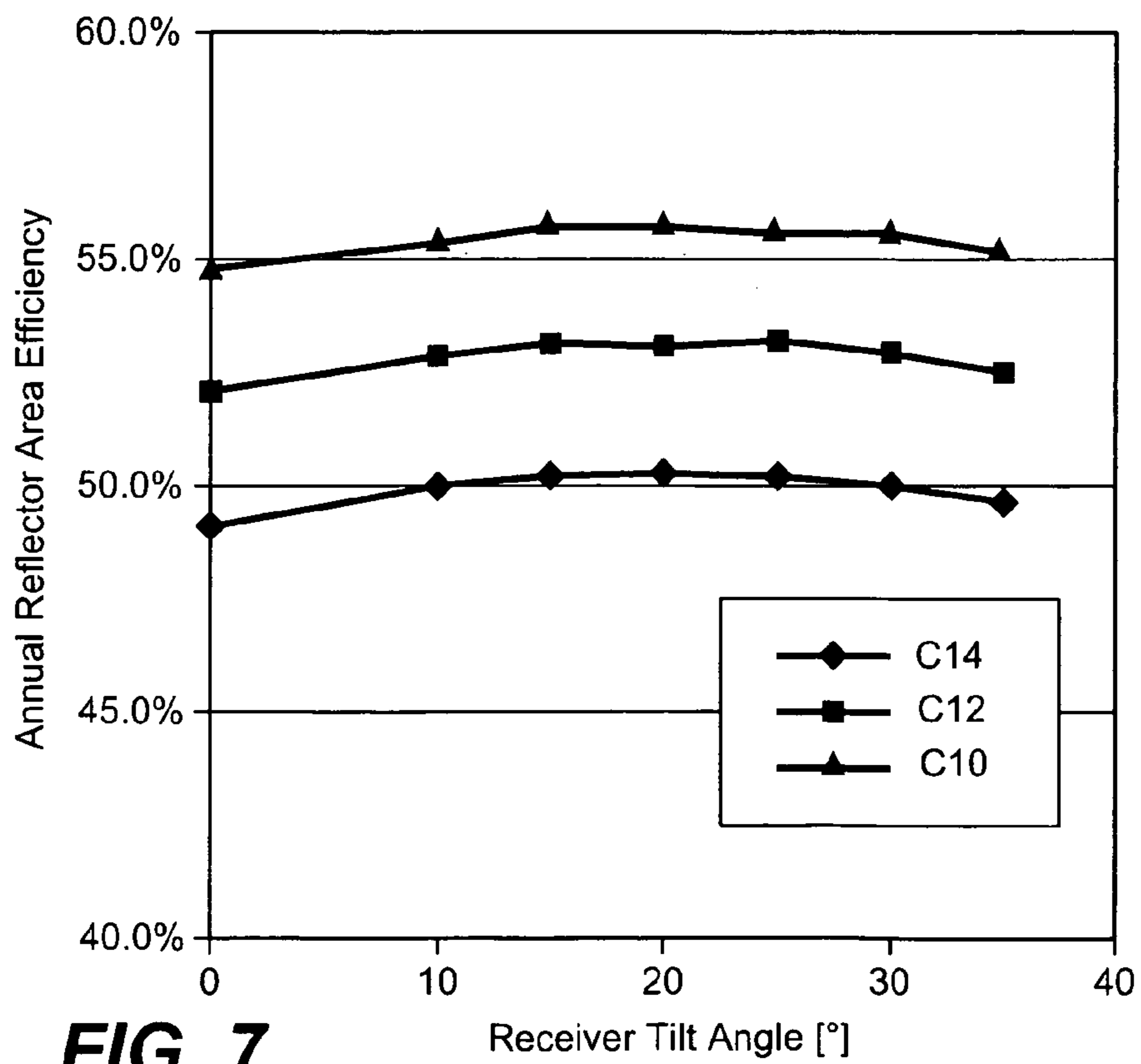


FIG. 5



**FIG. 6**



**FIG. 7**

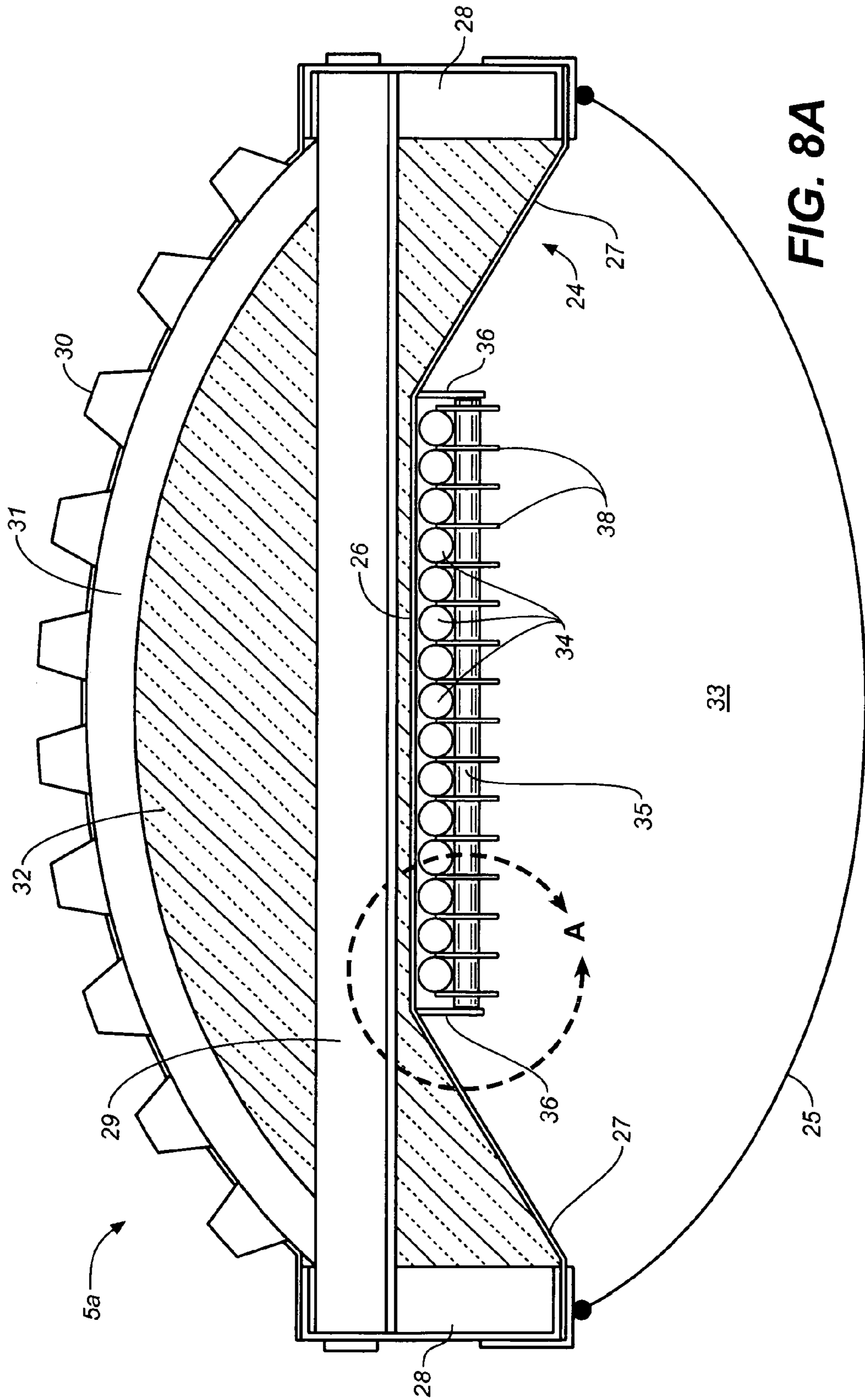
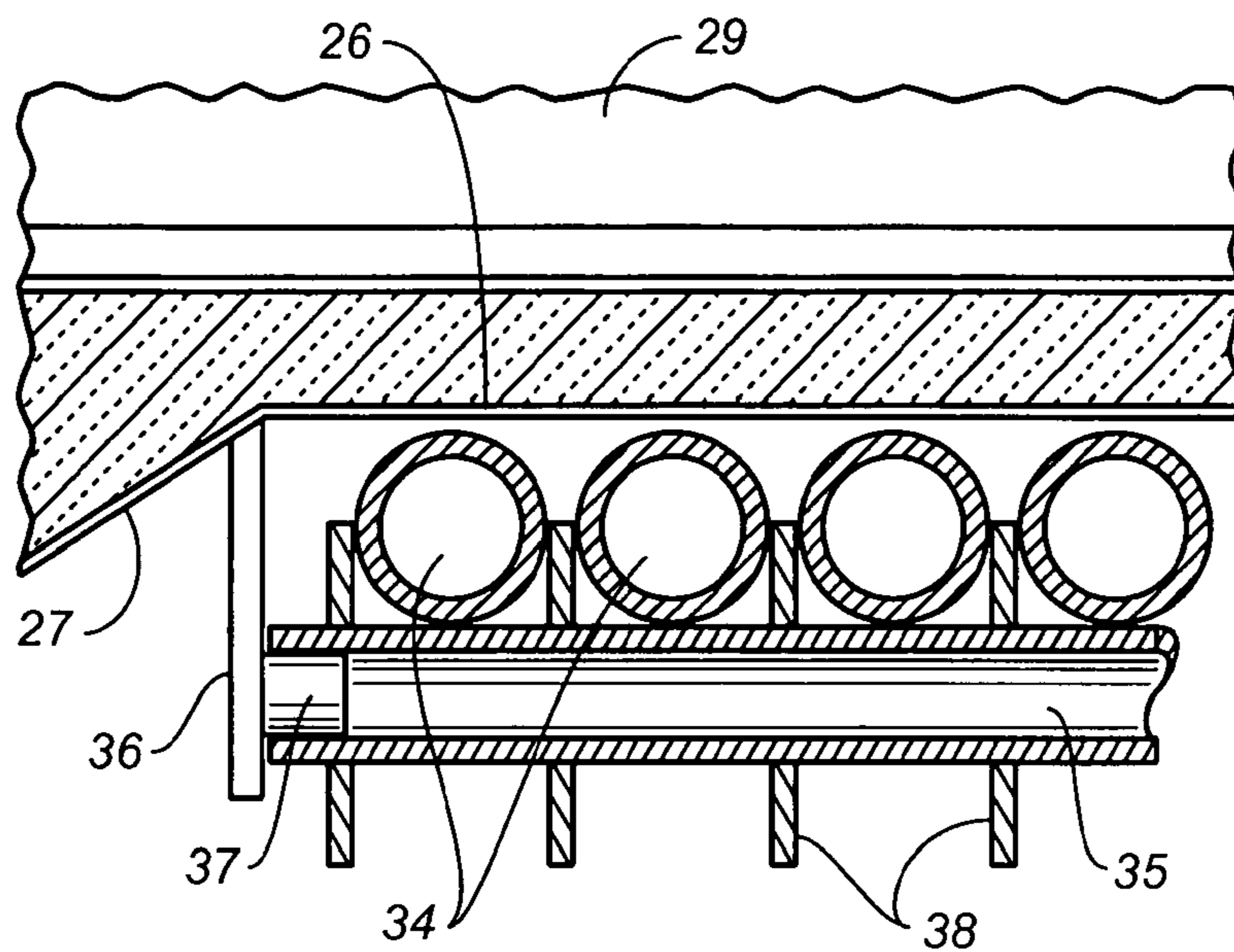
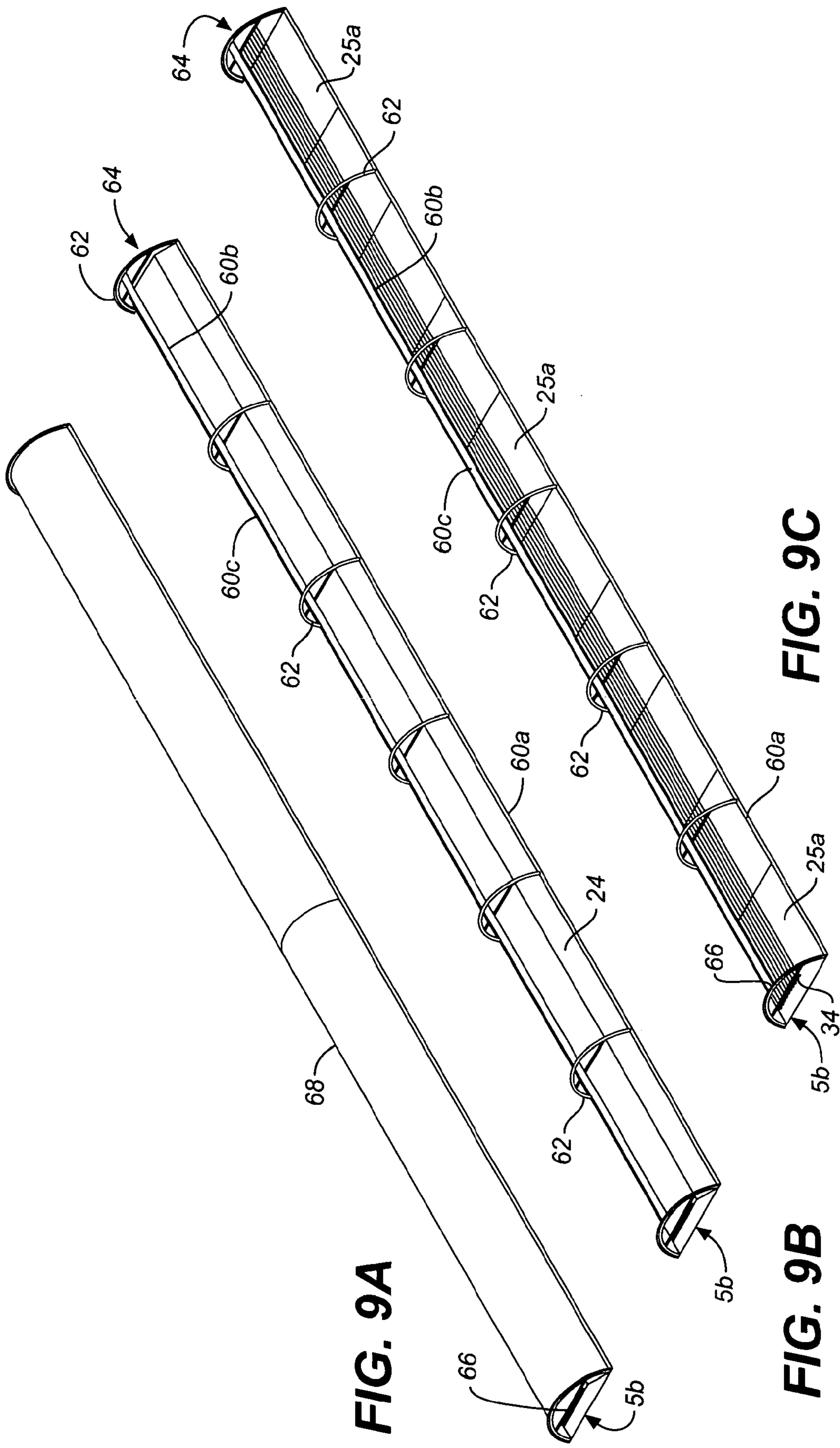


FIG. 8A



**FIG. 8B**

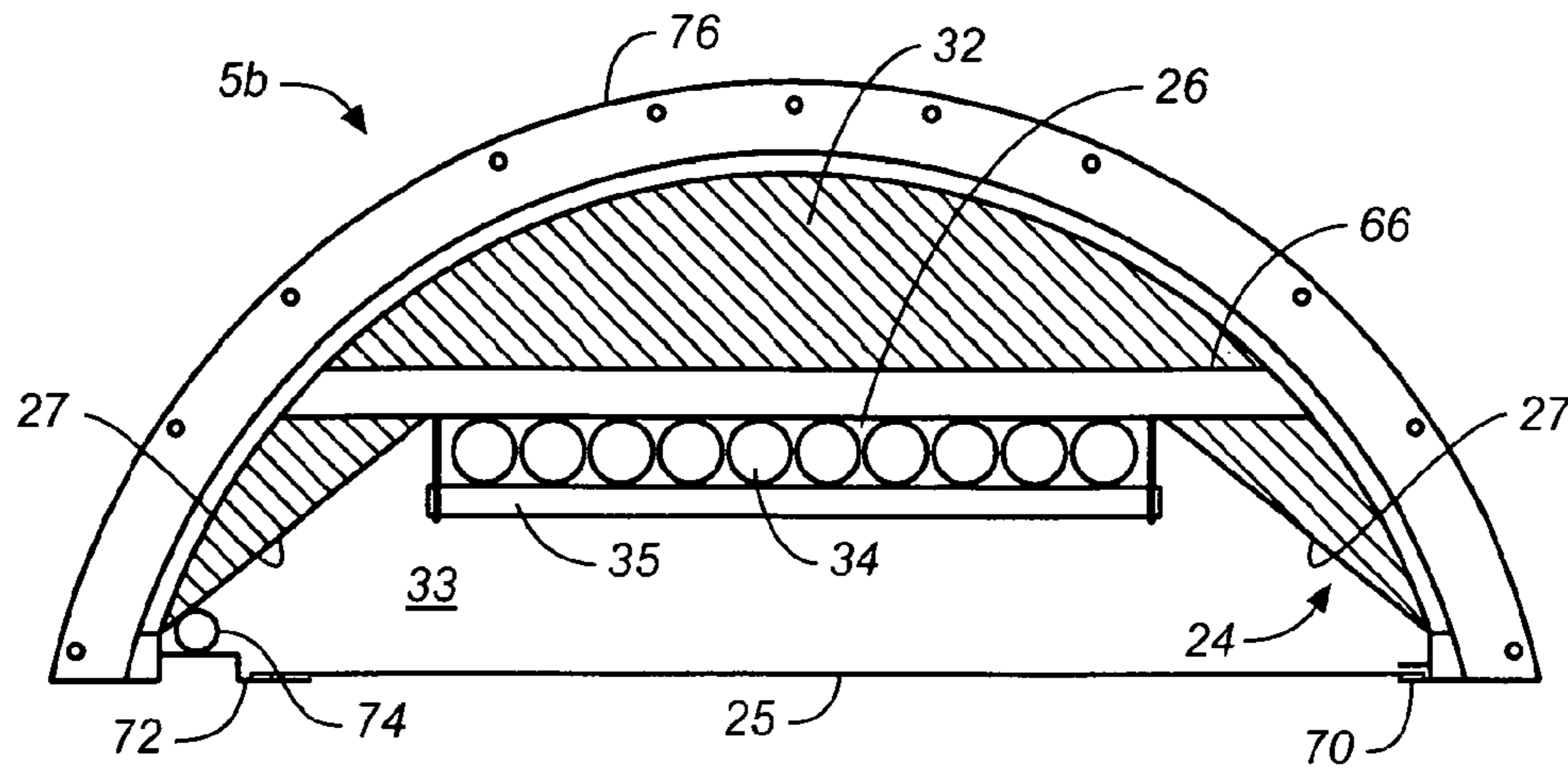


**FIG. 9A**

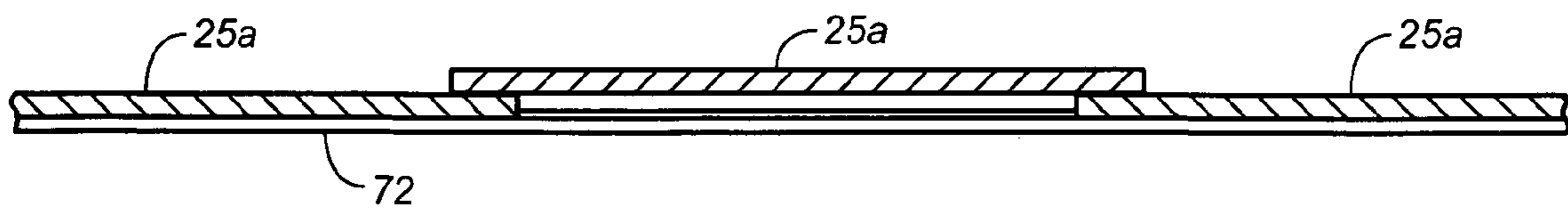
**FIG. 9B**

**FIG. 9C**

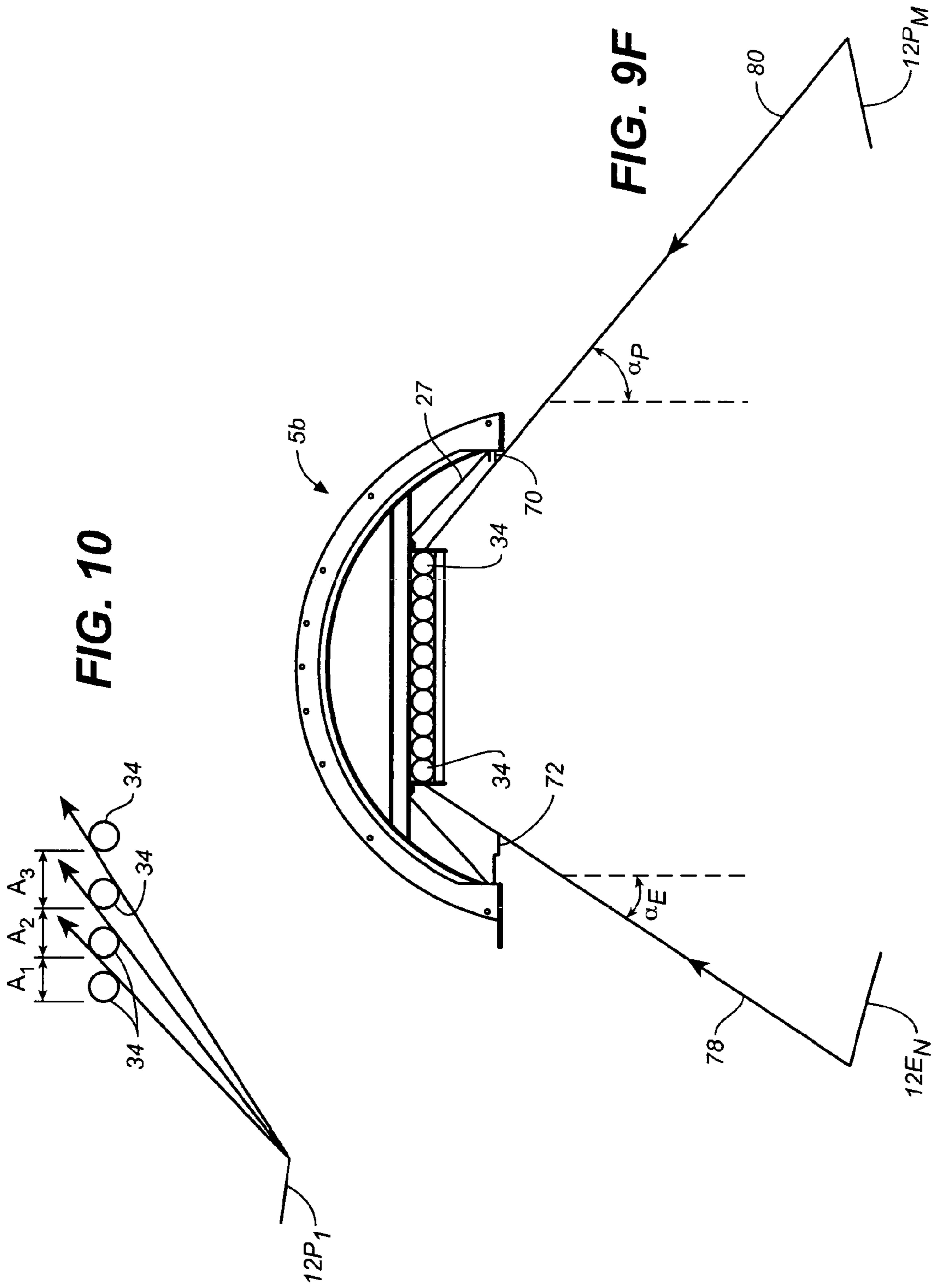


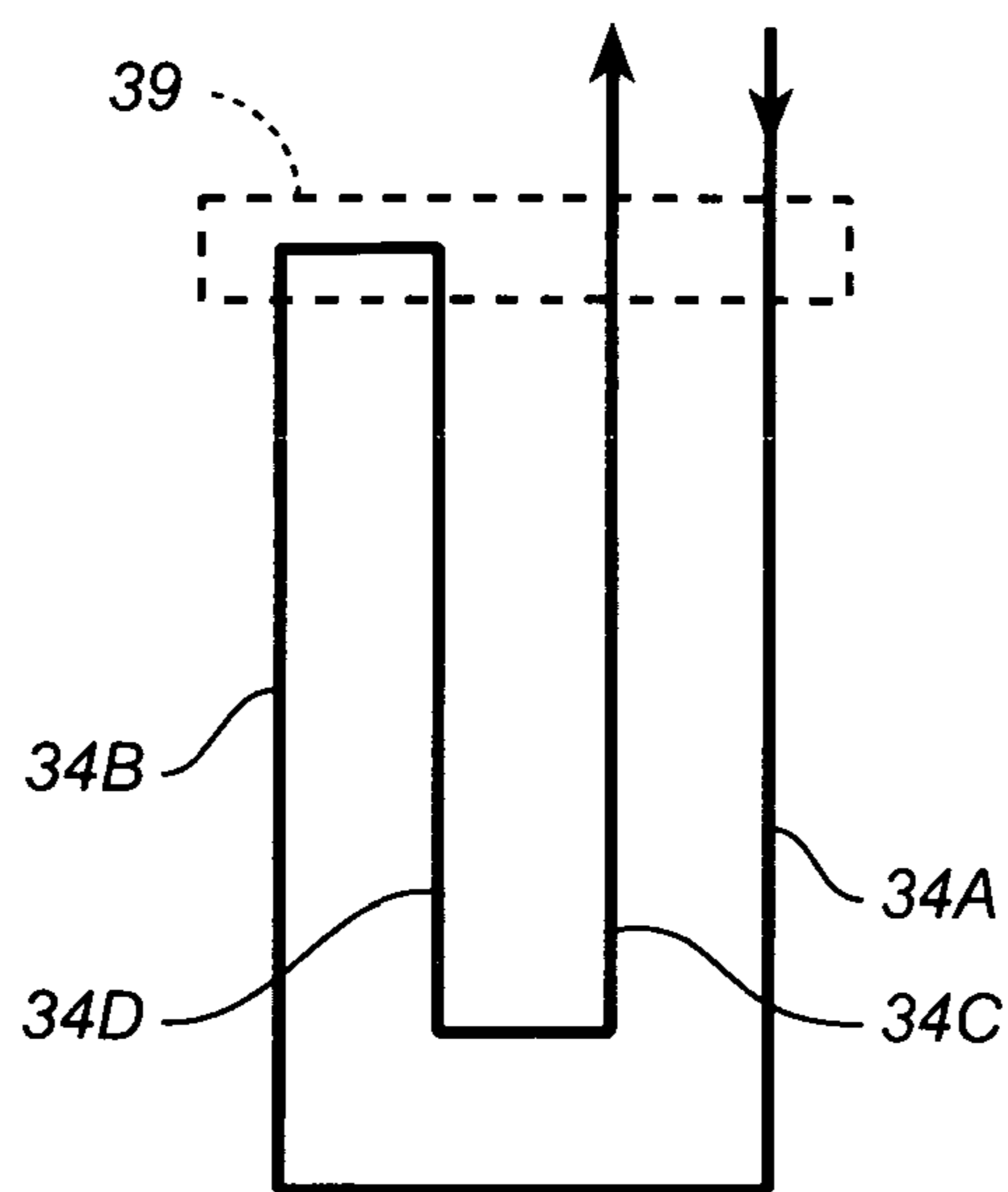
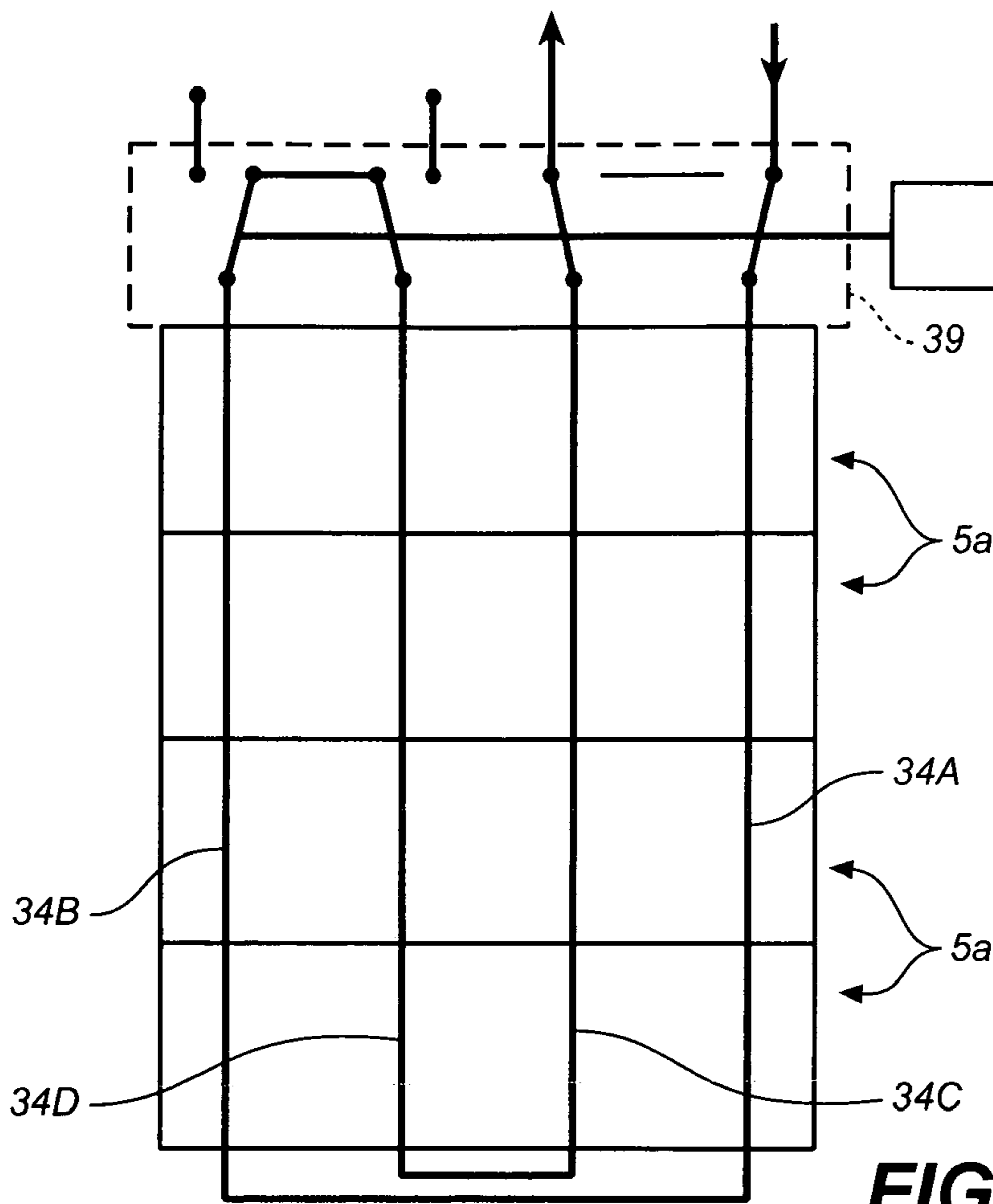


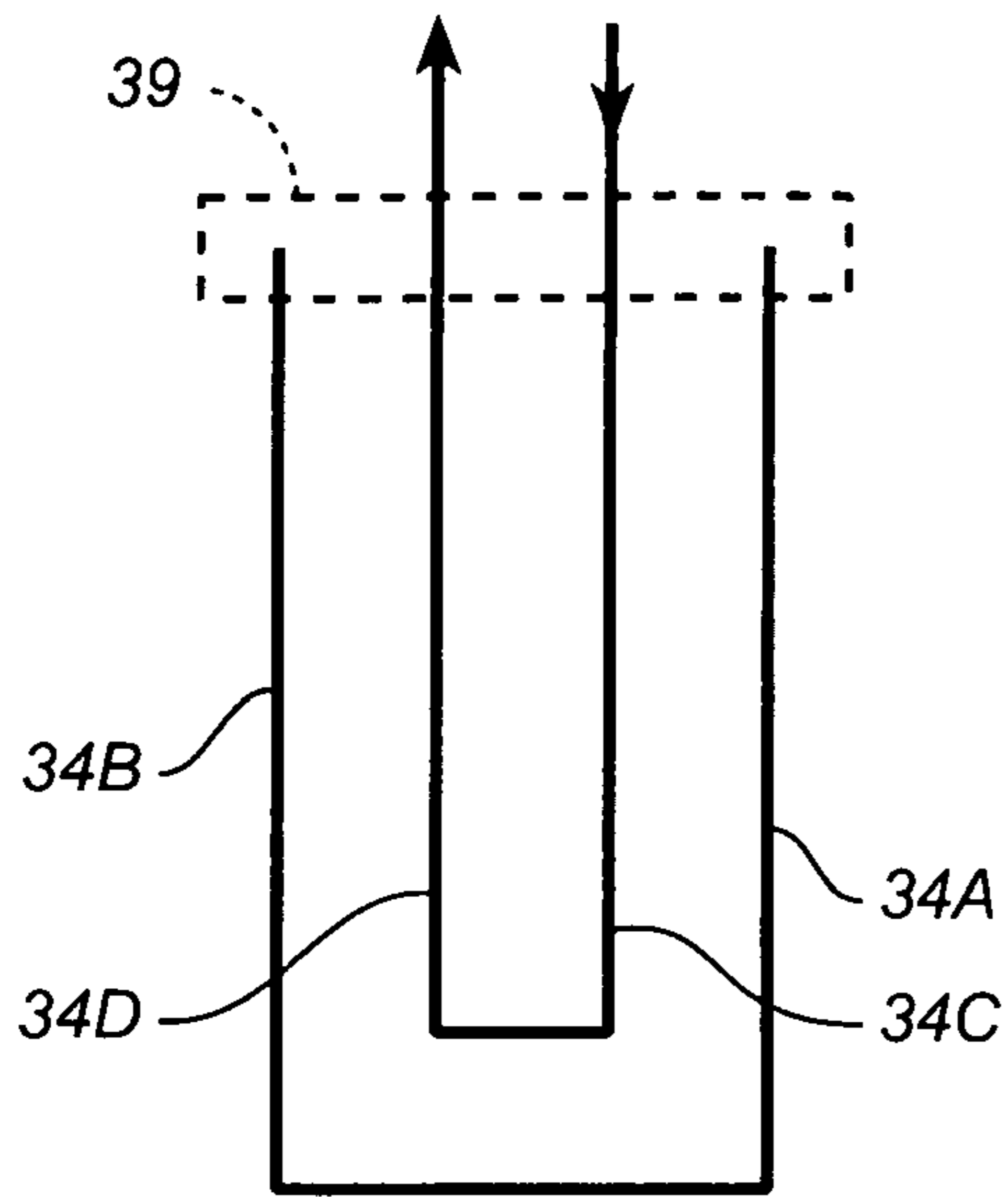
**FIG. 9D**



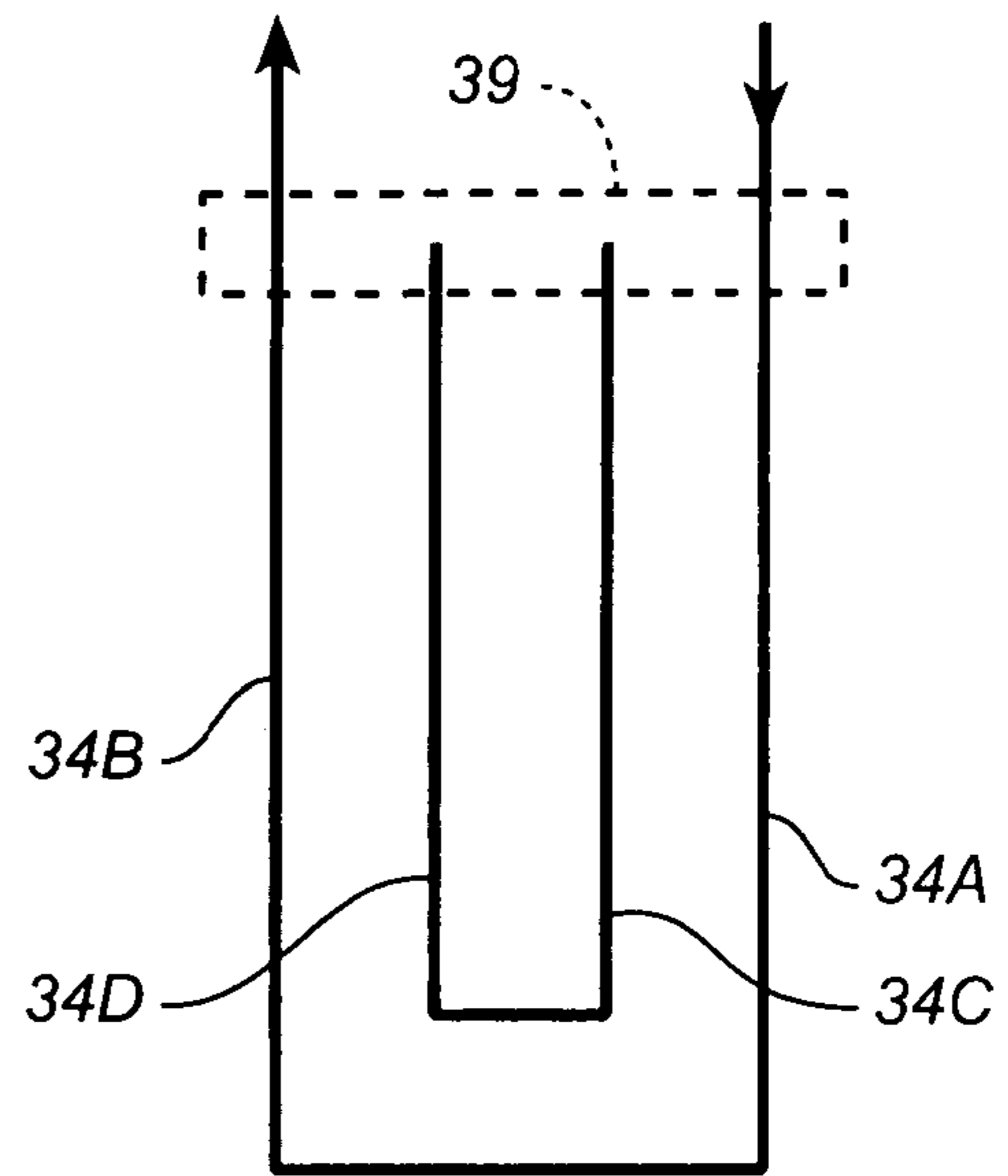
**FIG. 9E**



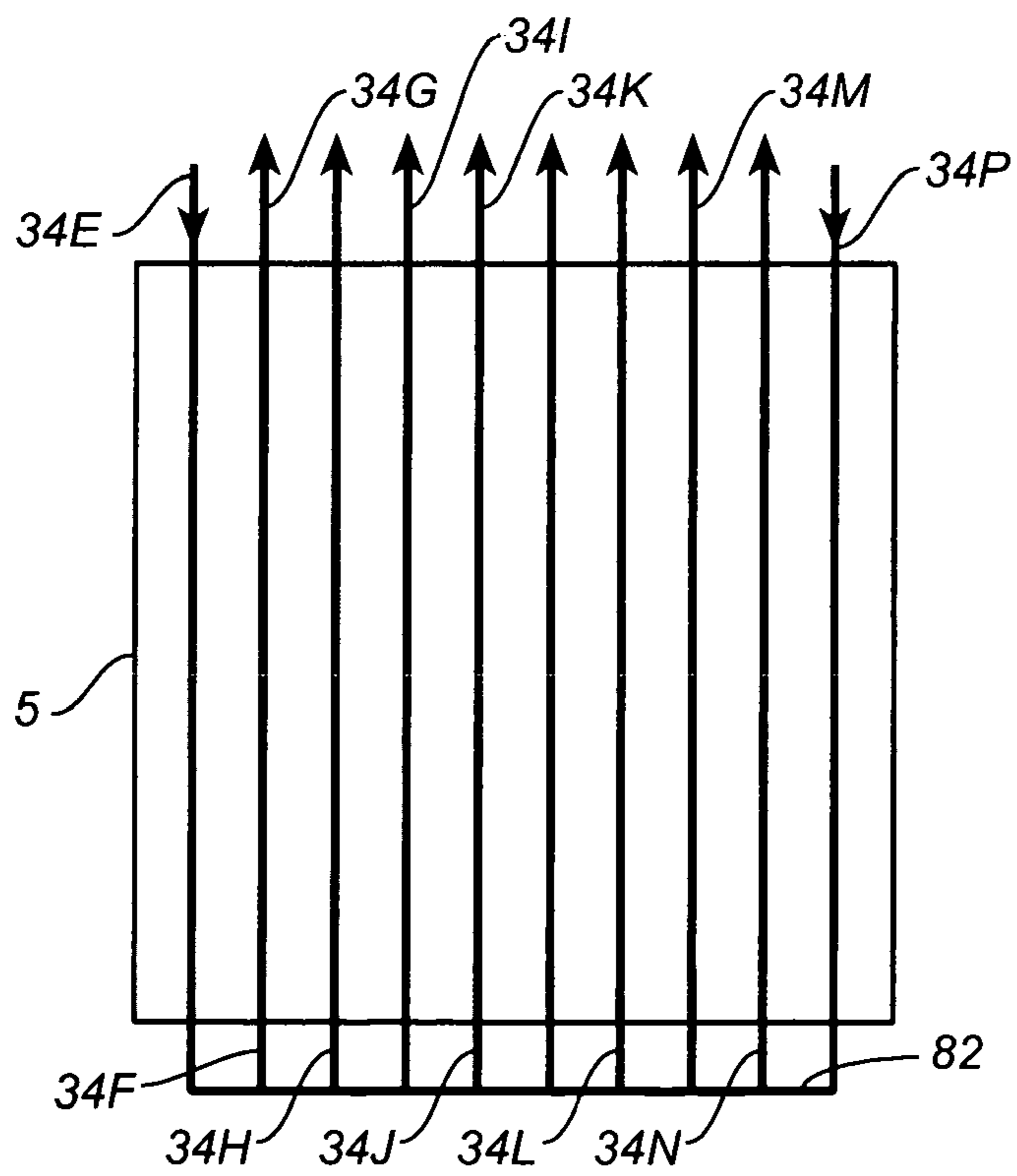




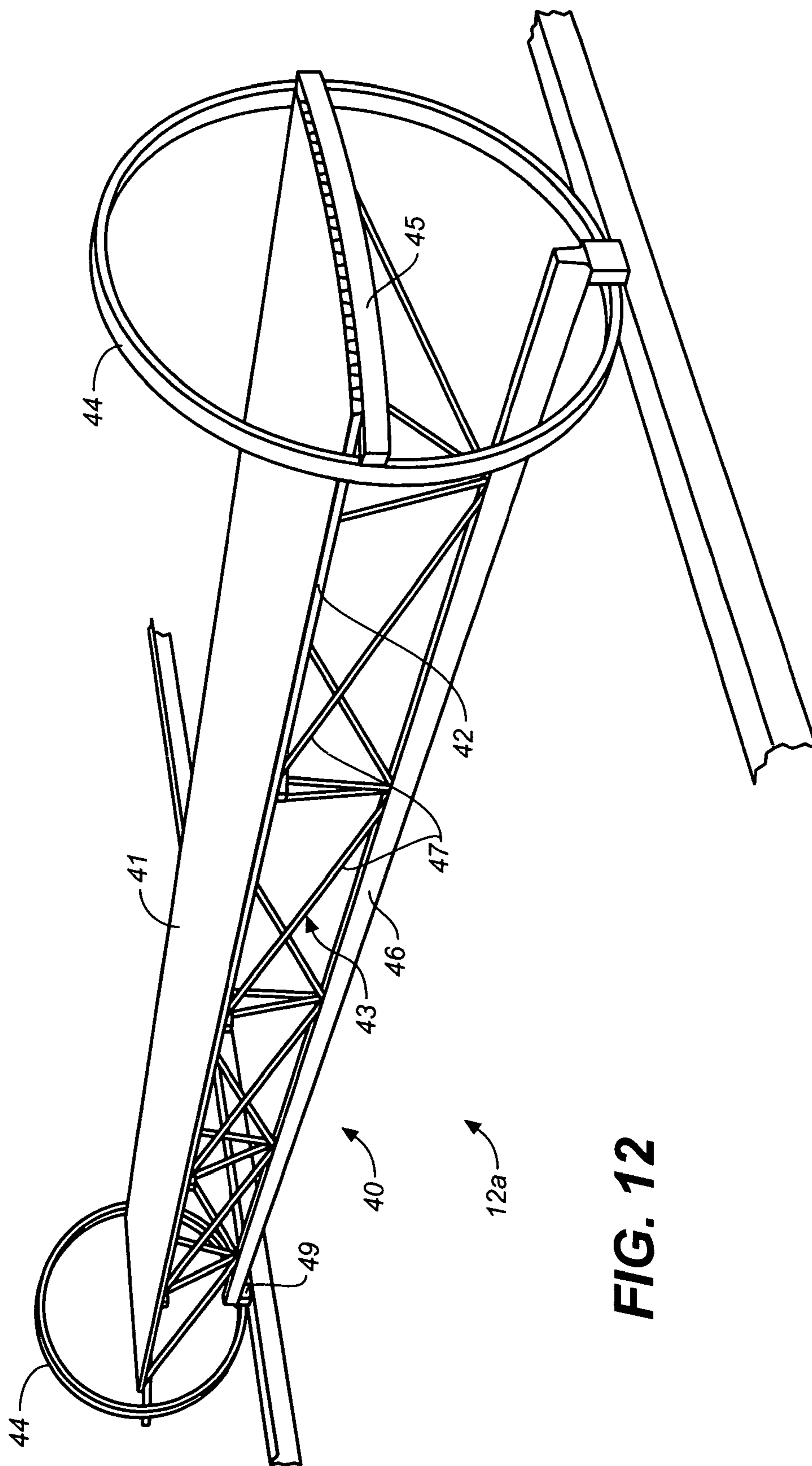
**FIG. 11C**



**FIG. 11D**



**FIG. 11E**



**FIG. 12**

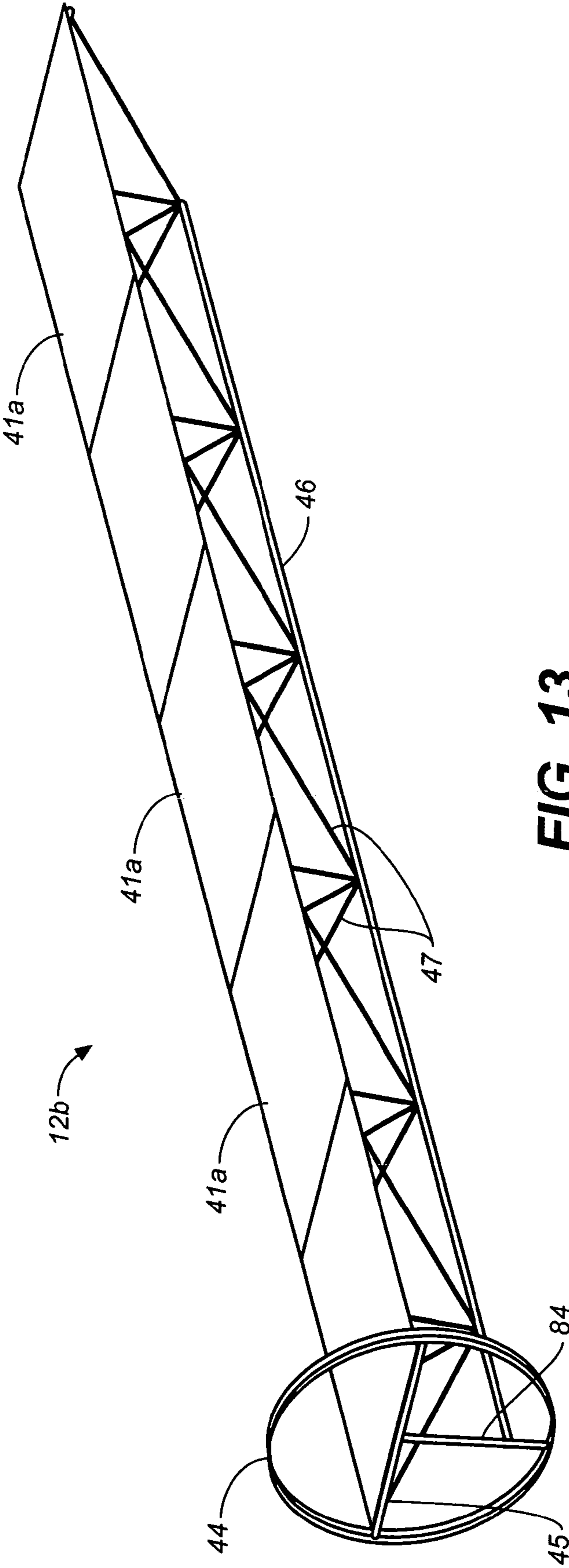
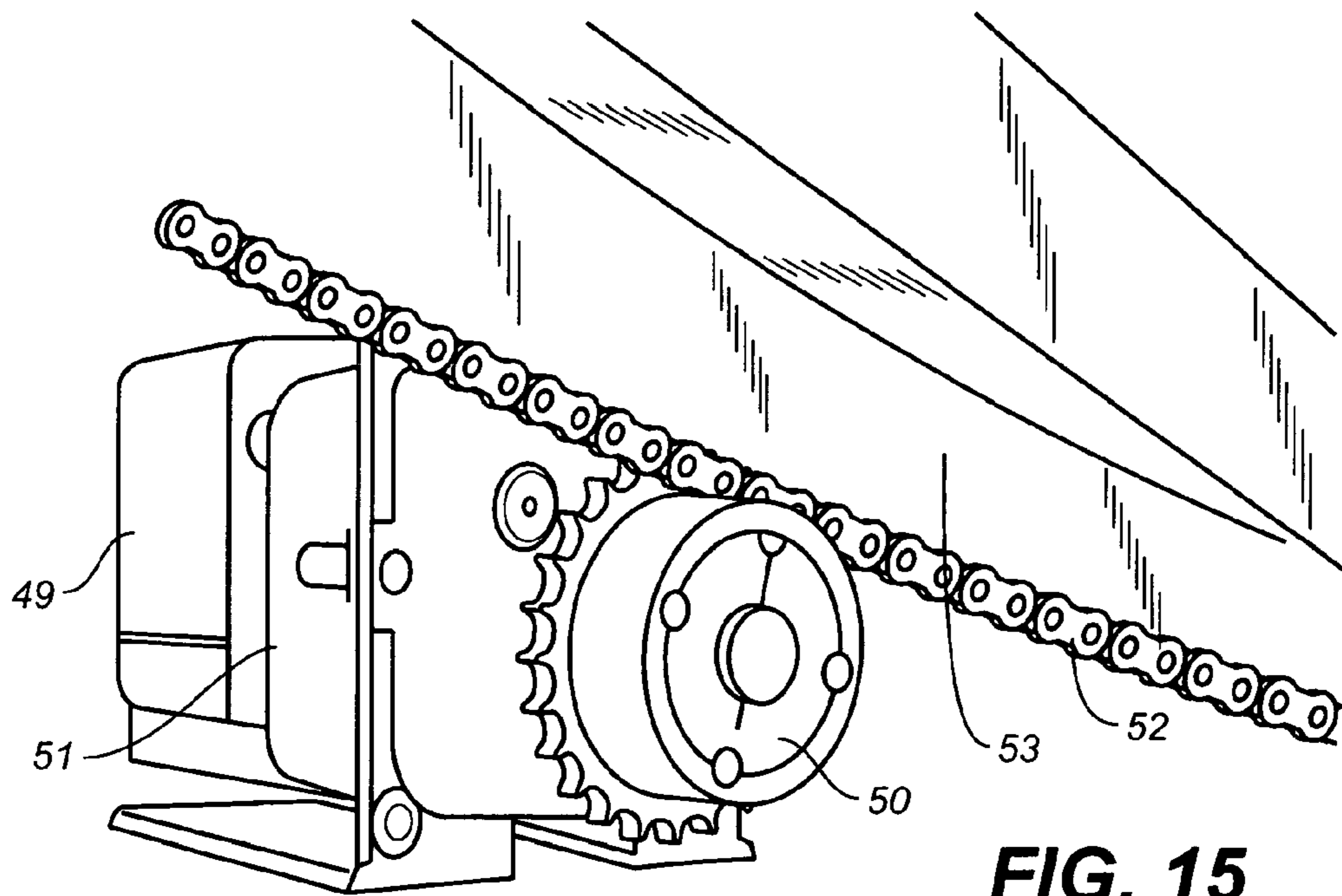
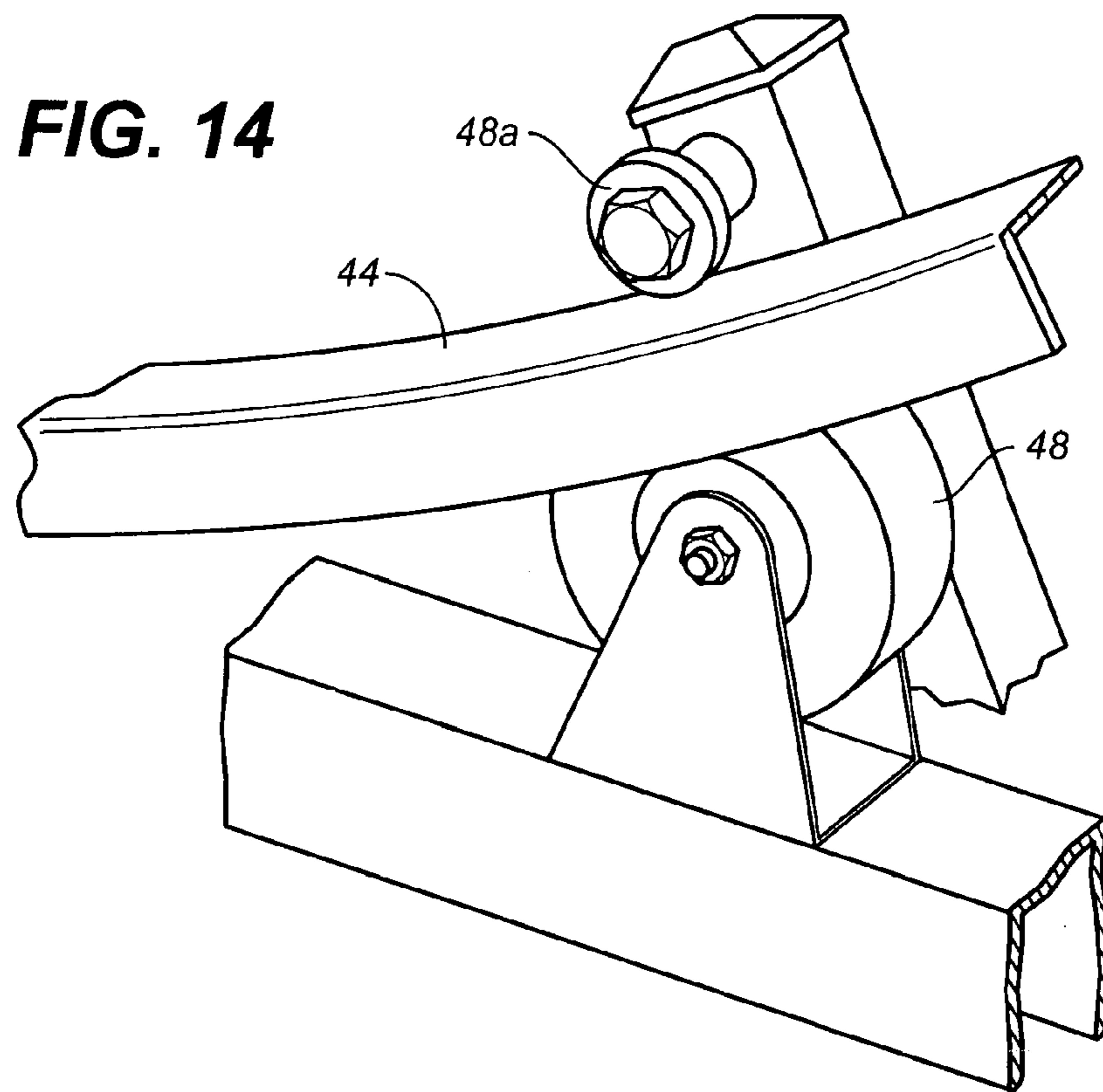


FIG. 13



**LINEAR FRESNEL SOLAR ARRAYS****CROSS-REFERENCE TO RELATED APPLICATIONS**

This application is a National Phase filing under 35 U.S.C. §371 of International Application No. PCT/US2008/010230, filed on Aug. 27, 2008, which claims the benefit of priority to U.S. Provisional Application Ser. No. 61/007,926 filed Aug. 27, 2007, entitled "Linear Fresnel Solar Arrays," which is incorporated by reference herein in its entirety. This application also claims the benefit of priority to U.S. patent application Ser. No. 12/012,920 filed Feb. 5, 2008, entitled "Linear Fresnel Solar Arrays and Components Therefor," U.S. patent application Ser. No. 12/012,829 filed Feb. 5, 2008, entitled "Linear Fresnel Solar Arrays and Receivers Therefor," and U.S. patent application Ser. No. 12/012,821 filed Feb. 5, 2008, entitled "Linear Fresnel Solar Arrays and Drives Therefor," each of which is incorporated by reference herein in its entirety.

**BACKGROUND OF THE INVENTION**

Solar energy collector systems of the type referred to as Linear Fresnel Reflector ("LFR") systems are relatively well known and are constituted by a field of linear reflectors that are arrayed in parallel side-by-side rows and are oriented to reflect incident solar radiation to a common elevated receiver. The receiver is illuminated by the reflected radiation, for energy exchange, and the receiver typically extends parallel to the rows of reflectors. Also, the receiver normally (but not necessarily) is positioned between two adjacent fields of reflectors; and  $n$  spaced-apart receivers may be illuminated by reflections from  $(n+1)$  or, alternatively,  $(n-1)$  reflector fields, in some circumstances with any one receiver being illuminated by reflected radiation from two adjacent reflector fields.

In most known LFR system implementations the receiver or receivers and the respective rows of reflectors are positioned to extend linearly in a north-south direction, with the reflector fields symmetrically disposed around the receivers and the reflectors pivotally mounted and driven through an angle approaching  $90^\circ$  to track east-west motion (i.e., apparent motion) of the sun during successive diurnal periods. This configuration requires that adjacent rows of reflectors be spaced-apart in order to avoid shading or blocking of one reflector by another and, thus, in order to optimize reflection of incident radiation. This limits ground utilization to approximately 70% and diminishes system performance due to exacerbated spillage at the receiver of radiation from distant reflectors.

As an alternative approach, a 1979 project design study (Ref Di Canio et al; Final Report 1977-79 DOE/ET/20426-1) proposed an east-west-extending LFR system. LFR systems having north-south orientations have typically been expected to outperform LFR systems having east-west orientations at most latitudes, however.

**SUMMARY OF THE INVENTION**

Disclosed herein are examples and variations of solar energy collector systems comprising an elevated linear receiver and first and second reflector fields located on opposite sides of, and arranged and driven to reflect solar radiation to, the receiver. Also disclosed herein are examples and variations of receivers and reflectors that may, in some variations, be utilized in the disclosed solar energy collector systems.

In a first aspect, a solar energy collector system comprises an elevated linear receiver extending generally in an east-west direction, a polar reflector field located on the polar side of the receiver, and an equatorial reflector field located on the equatorial side of the receiver. Each reflector field comprises reflectors positioned in one or more parallel side-by-side rows which extend generally in the east-west direction. The reflectors in each field are arranged to reflect incident solar radiation to the receiver during diurnal east-west motion of the sun and pivotally driven to maintain reflection of the incident solar radiation to the receiver during cyclic diurnal north-south motion of the sun. The polar reflector field comprises more reflector rows than the equatorial reflector field.

In a second aspect, another solar energy collector system comprises an elevated linear receiver extending generally in an east-west direction, a polar reflector field located on the polar side of the receiver, and an equatorial reflector field located on the equatorial side of the receiver. Each reflector field comprises reflectors positioned in one or more parallel side-by-side rows which extend generally in the east-west direction. The reflectors in each field are arranged to reflect incident solar radiation to the receiver during diurnal east-west motion of the sun and pivotally driven to maintain reflection of the incident solar radiation to the receiver during cyclic diurnal north-south motion of the sun. The reflectors in one or more outer rows of the equatorial reflector field have focal lengths greater than their respective distances to a solar radiation absorber in the receiver.

In a third aspect, another solar energy collector system comprises an elevated linear receiver extending generally in an east-west direction, a polar reflector field located on the polar side of the receiver, and an equatorial reflector field located on the equatorial side of the receiver. Each reflector field comprises reflectors positioned in one or more parallel side-by-side rows which extend generally in the east-west direction. The reflectors in each field are arranged to reflect incident solar radiation to the receiver during diurnal east-west motion of the sun and pivotally driven to maintain reflection of the incident solar radiation to the receiver during cyclic diurnal north-south motion of the sun. The receiver is tilted in the direction of the polar reflector field.

In a fourth aspect, a solar energy collector system comprises an elevated linear receiver comprising a solar radiation absorber and a window substantially transparent to solar radiation, and first and second reflector fields located on opposite sides of the receiver. Each reflector field comprises reflectors positioned in one or more parallel side-by-side rows which extend generally parallel to the receiver. The reflectors in each field are arranged and driven to maintain reflection of incident solar radiation to the absorber through the window during diurnal motion of the sun. The window comprises an anti-reflection coating having a maximum transmission of solar radiation at an angle of incidence differing from perpendicular incidence and selected to maximize an annualized solar radiation collection efficiency of the solar energy collector system.

These and other embodiments, features and advantages of the present invention will become more apparent to those skilled in the art when taken with reference to the following more detailed description of the invention in conjunction with the accompanying drawings that are first briefly described.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 shows schematically a portion of a Linear Fresnel Reflector ("LFR") solar collector system in accordance with



one variation of the present invention, the system having a single receiver and reflector fields located to the north and south of the receiver.

FIG. 2 shows a schematic representation of the LFR system of FIG. 1 as viewed in the direction of Arrow 3 as shown in FIG. 1.

FIG. 3 illustrates the relationship between the effective area of a reflector, the width of the reflector, and the angle of incidence of solar radiation incident on the reflector.

FIG. 4 shows schematically a portion of a LFR system as in FIG. 1 but with the receiver tilted from the horizontal in the direction of the polar reflector field.

FIG. 5 shows a more detailed representation of an example LFR system of the type shown in the previous figures but with two substantially parallel receivers.

FIG. 6 shows a schematic representation of an example receiver structure supported by a stanchion and stabilized by asymmetric guy wires.

FIG. 7 shows plots of annualized reflector area efficiency versus receiver tilt angle for three east-west LFR array configurations.

FIGS. 8A and 8B show schematic representations of an example receiver structure, with FIG. 8B showing a portion of the receiver structure which is encircled by circle A in FIG. 8A.

FIGS. 9A-9F show schematic representations of another example receiver structure, with FIGS. 9A-9C showing partial perspective views, FIG. 9D showing a transverse cross-sectional view, FIG. 9E showing detail of a window structure, and FIG. 9F illustrating the receiver structure's asymmetric aperture.

FIG. 10 shows a schematic representation of an example configuration of spacings between absorber tubes in a receiver.

FIGS. 11A-11E show example fluid flow arrangements through a receiver.

FIG. 12 shows a perspective view of a reflector according to one variation.

FIG. 13 shows a perspective view of a reflector according to another variation.

FIG. 14 shows on an enlarged scale a portion of a mounting arrangement for a reflector.

FIG. 15 shows on an enlarged scale a portion of a reflector and a drive system for the reflector according to one variation.

### DETAILED DESCRIPTION OF THE INVENTION

The following detailed description should be read with reference to the drawings, in which identical reference numbers refer to like elements throughout the different figures. The drawings, which are not necessarily to scale, depict selective embodiments and are not intended to limit the scope of the invention. The detailed description illustrates by way of example, not by way of limitation, the principles of the invention. This description will clearly enable one skilled in the art to make and use the invention, and describes several embodiments, adaptations, variations, alternatives and uses of the invention, including what is presently believed to be the best mode of carrying out the invention.

In addition, it must be noted that, as used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly indicates otherwise. Also, the term "parallel" is intended to mean "substantially parallel" and to encompass minor deviations from parallel geometries rather than to require that parallel rows of reflectors, for example, or any other parallel arrangements described herein be exactly parallel. The phrase

"generally in an east-west direction" as used herein is meant to indicate a direction orthogonal to the earth's rotation axis within a tolerance of  $\pm 45^\circ$ . For example, in referring to a row of reflectors extending generally in an east-west direction, it is meant that the reflector row lies orthogonal to the earth's rotation axis within a tolerance of  $\pm 45^\circ$ .

Disclosed herein are examples and variations of asymmetric east-west LFR solar arrays, receivers for receiving and capturing solar radiation collected by LFR solar arrays, and reflectors that may be used in LFR solar arrays. For convenience and clarity, asymmetric east-west LFR arrays, receivers, and reflectors are described in detail below in three separately labelled sections. This organization of the detailed description is not meant to be limiting, however. Any suitable receiver or reflector, disclosed herein, known to one of ordinary skill in the art, or later developed, may be used in the asymmetric arrays disclosed herein. Further, receivers and reflectors disclosed herein may be used, where suitable, in other east-west LFR solar arrays known to one of ordinary skill in the art or later developed, as well as in north-south LFR solar arrays known to one of ordinary skill in the art or later developed.

#### Asymmetric East-West LFR Arrays

An LFR solar array in which a receiver and rows of reflectors that are oriented generally in an east-west direction may have an asymmetric configuration as a result, for example, of asymmetric (i.e., differing) numbers of rows of reflectors on the polar and equatorial sides of the receiver and/or as a result of asymmetric spacing between rows on opposite sides of the receiver. As explained below, in some variations such asymmetries may improve the performance of the asymmetric east-west array compared to symmetric east-west LFR arrays or to north-south LFR arrays. Asymmetric numbers of rows, asymmetric row spacing, and examples of asymmetric east-west LFR configuration are described next in three subsections.

#### Asymmetric Numbers of Rows

Referring to FIGS. 1 and 2, an example east-west LFR solar array comprises an elevated receiver 5 extending generally in an east-west direction and positioned between two ground level reflector fields 10P and 10E. Reflector field 10P is located to the polar side of the receiver (i.e., to the northern side N in the case of a northern hemisphere system) and reflector field 10E is located to the equatorial side of the receiver (i.e., to the southern side S in the case of a northern hemisphere system). Reflector fields 10P and 10E comprise, respectively, parallel side-by-side reflector rows  $12P_1-12P_M$  and parallel side-by-side reflector rows  $12E_1-12E_N$ , which also extend in the generally east-west direction. The polar reflector rows are spaced apart by spacings  $15P_{x,x+1}$  where x identifies a particular row. As an example, spacing  $15P_{1,2}$  is identified in the figure. Similarly, the equatorial rows are spaced apart by spacings  $15E_{x,x+1}$ , with  $15E_{1,2}$  identified in the figure.

The reflectors in fields 10P and 10E are arranged and positioned to reflect incident solar radiation (e.g., ray 13) to the receiver 5 during diurnal east-west motion of the sun in the direction indicated by arrow 20 (FIG. 2). Additionally, the reflectors are pivotally driven to maintain reflection of the incident solar radiation to the receiver 5 during cyclic diurnal north-south motion of the sun in the (inclining and declining) directions indicated by arrow 21 (FIG. 1).

The inventors have discovered that in some cases the best annualized solar radiation collection efficiency for an east-west LFR array having a total number of substantially identical reflector rows M+N occurs for configurations in which the total number of rows M in the polar field 10P is greater

than the total number of rows  $N$  in the equatorial field **10E**. The inventors presently believe that this occurs because the reflectors in the polar field **10P** can in some cases provide a significantly greater effective reflector area and produce better focused images at the receiver than do reflectors in the equatorial field **10E** placed at similar (or even at shorter) distances from the receiver.

Referring to FIGS. **1** and **3**, the effective reflector width  $d$  provided by a reflector (e.g., reflector **12E<sub>N</sub>**) having a width  $D$  and oriented at an angle of incidence  $\theta$  between incident rays **13** and an axis  $Z$  perpendicular to the reflector is  $d=D \cos(\theta)$ . Thus, a reflector's effective area decreases as the angle of incidence increases. In addition, optical aberrations such as astigmatism, for example, increase as the angle of incidence increases. Such optical aberrations blur the focus of the solar radiation reflected by a reflector to the receiver and thus decrease collection efficiency.

The diurnal sun moves through an angle less than  $90^\circ$  in the north-south direction, as compared with an angle approaching  $180^\circ$  in the east-west direction. Hence, in contrast to north-south LFR arrays, the total pivotal movement imparted to each reflector in reflector fields **10P** and **10E** (FIG. **1**) is less than  $45^\circ$  during each diurnal period. As a consequence, the angles of incidence for reflectors in the polar field **10P** are always greater than those for the reflectors in equatorial field **10E**. The inventors have recognized that, as a further consequence, a reflector in the polar field will have greater effective area and produce better focus at the receiver than an identical reflector in the equatorial field positioned the same distance from the receiver. The inventors have discovered that these effects can be exploited to increase light collection efficiency in an east-west LFR solar array by putting more reflector rows in the polar field than in the equatorial field.

Improvements in collection efficiency resulting from putting more of a total number of rows of reflectors on the polar rather than on the equatorial side of a receiver in an east-west LFR array may be offset, to some extent, by the resulting increase in the number of reflectors at longer distances from the receiver and by the possibility of closely spacing equatorial rows (described below in the asymmetric spacing section). As the distance between a reflector and the receiver increases, the required focal length for the reflector and thus the size of the focused image at the receiver also increases. This can reduce collection efficiency if the focused spot is bigger than the receiver, for example. In addition, the angle of incidence on a horizontally oriented receiver surface (e.g., a transparent window) made by rays of light reflected by one of the reflectors to the receiver increases as the distance between the reflector and the receiver increases. This can increase the loss of collected light due to reflection at the receiver. Consequently, the optimal number of rows of reflectors in the equatorial field is typically, though not necessarily, greater than zero.

Improvements in collection efficiency resulting from putting more of a total number of rows of reflectors on the polar rather than on the equatorial side of a receiver in an east-west LFR array may also be affected by the height at which the receiver is positioned, the orientation (tilt) of the receiver from horizontal, and the latitude (angular distance north or south from the equator) at which the array is located. Generally, the resulting improvements in collection efficiency are expected to increase with latitude and to be more pronounced for shorter than for taller receivers. Collection efficiency can be further increased by tilting the receiver by an angle  $\phi$  (FIG. **4**) from the horizontal to face the polar reflector field. Tilting the receiver in the polar direction may further increase the optimal number of rows of reflectors in the polar field.

#### Asymmetric Row Spacings

Referring again to FIG. **1**, the inventors have additionally recognized that, as a consequence of the generally east-west orientation of the array, the reflectors in the equatorial reflector field **10E** will at all times be disposed at an angle to the horizontal that is substantially more acute than that of the reflectors in polar reflector field **10P**. Hence, the potential for shading of reflectors in equatorial field **10E** will be small relative to that applicable to the reflectors in polar field **10P**.

This permits closer spacing of the equatorial rows than of the polar rows and thus results in a reduction in the total field area relative to that required for an array in which reflector rows are arranged with symmetric spacing around a receiver, as in typical north-south LFR systems. Also, because of the close-to-horizontal disposition of the reflectors in the equatorial field **10E** and the close-packing of reflector rows that it permits, equatorial rows of reflectors can be located closer to the receiver than corresponding rows in a north-south LFR array or than corresponding rows in the polar field **10P**, thus decreasing focused image size and reducing radiation spillage at the receiver. The inventors have discovered that these effects can be exploited to increase annualized solar radiation collection efficiency in an east-west LFR solar array by asymmetrically spacing the rows of reflectors on opposite sides of the receiver.

Rows on opposite side of the receiver may in some variations be advantageously asymmetrically spaced, for example, by maintaining constant polar row spacings  $15P_{x,x+1}$  and constant equatorial  $15E_{x,x+1}$ , with  $15P_{x,x+1} > 15E_{x,x+1}$ ; by maintaining a constant equatorial spacing  $15E_{x,x+1}$  that is smaller than all polar spacings  $15P_{x,x+1}$ , with polar spacings  $15P_{x,x+1}$  increasing with distance from the receiver; or by having polar  $15P_{x,x+1}$  and equatorial row spacings  $15E_{x,x+1}$ , each increase with distance from the receiver with equatorial row spacings  $15E_{x,x+1}$ , smaller than corresponding (i.e., between corresponding row numbers) polar rows spacings  $15P_{x,x+1}$ . More generally, asymmetric row spacing as used herein is intended to include all variations in which some or all corresponding rows on opposite sides of a receiver are not symmetrically spaced. Asymmetric spacing may, in some variations, result in some or all of the equatorial rows being positioned closer to the receiver than corresponding polar rows.

Improvements in collection efficiency resulting from asymmetrically spacing the rows of reflectors on opposite sides of the receiver may be affected by the height at which the receiver is positioned, the orientation (tilt) of the receiver from horizontal, and the latitude (angular distance north or south from the equator) at which the array is located. Generally, the resulting improvements in collection efficiency are expected to increase with latitude and to be more pronounced for shorter than for taller receivers.

The east-west LFR arrays disclosed herein in which reflector rows on opposite sides of a receiver are asymmetrically spaced as described above may, in some variations, achieve reflector to ground area ratios greater than about 70%, greater than about 75%, or greater than about 80%.

Asymmetric row spacing is further described in International Patent Application Serial No. PCT/AU2007/001232, titled "Energy Collection System Having East-West Extending Linear Reflectors," filed 27 Aug. 2007, assigned to Solar Heat and Power Pty Ltd., for which David Mills and Peter Le Lievre are inventors; incorporated herein by reference in its entirety.

#### Example Array Configurations

Referring now to FIG. **5**, another example LFR system of the type shown in the previous figures comprises polar **10P** and equatorial **10E** reflector fields comprising reflectors **12a**

aligned (and, e.g., interconnected) in parallel rows **12P**, **12E** that extend generally in an east-west direction. In addition, this example LFR system comprises two parallel receivers **5**, each of which is constituted by aligned (and, e.g., interconnected) receiver structures **5a**. Reflectors **12a** may be driven collectively or regionally, as rows or individually, to track motion of the sun. Reflectors **12a** are oriented to reflect incident radiation to respective ones of the receivers **5** in the manner described with reference to the previous figures.

A complete LFR system might occupy a ground area of, for example, about  $5 \times 10 \text{ m}^2$  to about  $25 \times 10^6 \text{ m}^2$ . The system as illustrated in FIG. **5** may be considered as a portion only of a larger LFR system having a plurality of receivers arranged side-by-side and parallel to each other.

Reflectors **12a** may be any suitable reflector described herein (e.g., below in the reflectors section), known to one or ordinary skill in the art, or later developed. Suitable reflectors may include, for example, those disclosed in International Patent Applications numbered PCT/AU2004/000883 and PCT/AU2004/000884, both of which are incorporated herein by reference in their entirety.

Suitable reflectors may have, for example, circular or parabolic cross sections providing approximately a line focus, and may have focal lengths of, for example, about 10 to about 25 meters (i.e., radii of curvature of about 20 meters to about 50 meters for reflectors with circular cross section). In some variations, the focal length of a reflector approximately matches the distance from the reflector to the receiver. In other variations, the focal length of a reflector is about 5% to about 20%, or from about 5% to about 15%, or from about 10% to about 15% greater than the distance from the reflector to the receiver. The inventors have discovered that the solar radiation collection efficiency of an east-west LFR solar array can be improved by using reflectors having such focal lengths greater than the distance to the receiver, particularly for the equatorial rows farthest from the receiver. The collection efficiency of outer equatorial rows may be improved in this manner by, for example more than 5%.

Reflectors **12a** may have, for example, lengths of about 10 meters to about 20 meters and widths of about 1 meter to about 3 meters. Any suitable reflector dimensions may be used, however. In one variation, reflectors **12a** have lengths of about 12 meters and widths of about 2 meters. In another variation, reflectors **12a** have lengths of about 16 meters and widths of about 2 meters.

Each row **12P**, **12E** of reflectors and each receiver **5** may have, for example, an overall length of about 200 to about 600 meters. Any suitable row and/or receiver length may be used, however. In some variations, groups of adjacent reflectors in a row are interconnected to form row segments driven collectively by one or more motors. Such a row segment may comprise, for example, 2, 4, 6, or any suitable number of reflectors.

Receivers **5** may be any suitable receiver described herein (e.g., below in the receiver section), known to one or ordinary skill in the art, or later developed. Suitable receivers may include, for example, those disclosed in International Patent Application numbered PCT/AU2005/000208, which is incorporated herein by reference in its entirety. Receivers **5** may be, for example photovoltaic receivers which absorb incident solar radiation and convert it to electricity, or thermal receivers which absorb incident solar radiation to heat a working or heat exchange fluid passing through the receiver. Receivers **5** may have a horizontal orientation (e.g., a horizontally oriented aperture and/ or absorber) as shown in FIGS. **1** and **5**, for example, or a tilted orientation (e.g., an aperture and/or absorber tilted toward either the polar or the equatorial reflec-

tor field) as shown, for example, in FIG. **4**. Suitable receivers may have, for example, absorbers (e.g., groups of tubes or flat plates) having a width (i.e., perpendicular to the long axis of the receiver) of about 0.3 meters to about 1 meter, or any other suitable width.

Receivers **5** may optionally be formed from interconnected receiver structures **5a** as shown, for example, in FIG. **5**. Receiver structures **5a** may have lengths of, for example, about 8 meters to about 20 meters and overall widths of about 0.5 meters to about 1.5 meters.

Receivers **5** might typically be spaced apart by 20 to 35 meters, for example, but any suitable receiver spacing may be used. The receivers may be supported, for example, with their absorbers positioned at a height of about 10 meters to about 20 meters above the reflectors by, for example, stanchions **22** as shown in FIG. **5** and FIG. **6**. Such stanchions may be stayed by ground-anchored guy wires **23** as shown in FIG. **5**, for example. The inventors have discovered that the use of asymmetric guy wires (i.e., guy wires of at least two different lengths) such as guys wires **23P**, **23E** shown in FIG. **6**, for example, may advantageously stabilize stanchion **22** and receiver **15** against oscillations. Such stabilization results from the different length guy wires providing different resonance frequencies to the stanchion/receiver structure. The different resonances couple to and damp each other.

Although the example array depicted in FIG. **5** has equal numbers (i.e., 6) of reflector rows in each polar **10P** and equatorial **10E** reflector field, other variations may include different numbers of rows in the polar and equatorial reflector fields and may include more or fewer than the 12 total rows per receiver shown. In one example, each receiver has 10 associated rows of reflectors, with 6 rows in the polar field and 4 rows in the equatorial field. In another example, each receiver has 10 associated rows, with 7 rows in the polar field and 3 rows in the equatorial field. In another example, each receiver has 12 associated rows, with 8 rows in the polar field and 4 rows in the equatorial field. In another example, each receiver has 14 associated rows, with 9 rows in the polar field and 5 rows in the equatorial field. In yet another example, each receiver has 14 associated rows, with 10 rows in the polar field and 4 rows in the equatorial field. Generally, any suitable total number of rows and any suitable distribution of the rows between polar and equatorial fields may be used.

Although the rows of reflectors in the example array depicted in FIG. **5** are spaced at uniform intervals in the polar **10P** and equatorial fields **10E**, in other variations the spacings may be asymmetric in any of the manners described above. Generally, any suitable combination of asymmetric numbers of rows in polar and equatorial reflector fields may be used in combination with any suitable asymmetric row spacing. In addition, any suitable asymmetric number of rows in polar and equatorial reflector fields may be used with symmetric row spacings. Also, any suitable symmetric (i.e., equal) number of rows in polar and equatorial reflector fields may be used with any suitable asymmetric row spacing.

As noted above, in some variations tilting the receiver toward the polar reflector field further increases solar radiation collection efficiency. In some variations, the receiver is tilted toward the polar field at, for example, an angle to the horizontal of about  $5^\circ$  to about  $35^\circ$ , of about  $10^\circ$  to about  $30^\circ$ , of about  $15^\circ$  to about  $35^\circ$ , or about  $15^\circ$  to about  $20^\circ$ .

FIG. **7** shows three plots of annualized solar radiation collection efficiency versus receiver tilt angle generated with a ray-tracing calculation of three different array configurations. Curve **C10** shows the result for an array having a total of 10 reflector rows, curve **C12** shows the results for an array having 12 reflector rows, and curve **C14** shows the results for

an array having 14 reflector rows. For each tilt angle, the optimal distribution of reflector rows was determined. At 15°, for example, the C10 array had 3 equatorial rows, the C12 array had 4 equatorial rows, and the C14 array had 5 equatorial rows. At 20°, the C10 array had 3 equatorial rows, the C12 array had 4 equatorial rows, and the C14 array had 4 equatorial rows. In the calculation, all reflector rows are approximately 2.3 meters wide, the absorber has a width of about 0.60 meters and is located about 15 meters above the reflectors, and the same rows in the arrays of C10, C12, and C14 have the same positions with respect to the receiver. The spacings between polar rows increase with distance from the receiver from about 2.7 meters for the spacing between mirror center lines in the first two rows to about 5.2 meters between the ninth and tenth rows from the receiver. The spacings between mirror center lines in the equatorial rows have a constant value of about 2.6 meters.

As noted above, the optimal distribution of reflector rows between equatorial and polar reflector fields may vary with latitude and other factors. Hence, the tilted receiver examples just described are intended to be illustrative rather than limiting.

#### Receivers

The receivers **5** and receiver structures **5a** and **5b** described in this section may, in some variations, be suitable for use in the east-west LFR solar arrays disclosed herein, in east-west and/or north-south LFR solar arrays known to one of ordinary skill in the art, and/or in east-west or north-south LFR solar arrays later developed.

Referring to FIGS. **6**, **8A** and **8B**, in some variations a receiver structure **5a** comprises an inverted trough **24** which might typically be formed from stainless steel sheeting and which, as best seen in FIG. **8**, has a longitudinally extending channel portion **26** and flared side walls **27** that, at their margins, define the transverse width of an aperture of the inverted trough through which solar radiation incident from the reflectors may enter the trough. In the illustrated variation, the trough **24** is supported and provided with structural integrity by side rails **28** and transverse bridging members **29**, and the trough is surmounted by a corrugated steel roof **30** that is carried by arched structural members **31**.

In the illustrated variation, the void between the trough **24** and the roof **30** is filled with a thermal insulating material **32**, typically a glass wool material, and desirably with an insulating material that is clad with a reflective metal layer. The function of the insulating material and the reflective metal layer is to inhibit upward conduction and radiation of heat from within the trough. Other forms and configurations of insulation may be used, however.

A longitudinally extending window **25** is provided to interconnect the side walls **27** of the trough. The window is formed from a sheet of material that is substantially transparent to solar radiation and it functions to define a closed (heat retaining) longitudinally extending cavity **33** within the trough. Window **25** may be formed from glass, for example. Although window **25** is depicted in FIG. **6** and FIG. **8** as having a convex curved shape, this is not necessary and in other variations window **25** may be flat, for example.

In the receiver structure as illustrated in FIGS. **6**, **8**, and **9**, longitudinally extending (e.g., stainless steel or carbon steel) absorber tubes **34** are provided for carrying working or heat exchange fluid (typically water or, following heat absorption, water-steam or steam). The actual number of absorber tubes may be varied to suit specific system requirements, provided that each absorber tube has a diameter that is small relative to the dimension of the trough aperture between the side walls **28** of the trough, and the receiver structure might typically

have between about six and about thirty absorber tubes **34** supported side-by side within the trough.

The actual ratio of the absorber tube diameter to the trough aperture dimension may be varied to meet system requirements but, in order to indicate an order of magnitude of the ratio, it might typically be within the range of about 0.01:1.00 to about 0.1:1.00. Each absorber tube **34** might have an outside diameter of about 25 millimeters to about 160 millimeters, for example. In one variation, the absorber tubes have outside diameters of about 33 mm. In another variation the absorber tubes have outside diameters of about 60 mm.

With the above described arrangement the plurality of absorber tubes **34** may effectively simulate a flat plate absorber, as compared with a single-tube collector in a concentrating trough. This provides for increased operating efficiency, in terms of a reduced level of heat emission from the upper, non-illuminated circumferential portion of the absorber tubes. Moreover, by positioning the absorber tubes in the inverted trough in the manner described, the underside portion only of each of the absorber tubes is illuminated with incident radiation, this providing for efficient heat absorption in absorber tubes that carry steam above water.

In the illustrated variation, the absorber tubes **34** are freely supported by a series of parallel support tubes **35** which extend orthogonally between side walls **36** of the channel portion **26** of the inverted trough, and the support tubes **35** may be carried for rotational movement by spigots **37**. This arrangement accommodates expansion of the absorber tubes and relative expansion of the individual tubes. Disk-shaped spacers **38** are carried by the support tubes **35** and serve to maintain the absorber tubes **34** in spaced relationship. Other arrangements for supporting the absorber tubes in the inverted trough may also be used.

In some variations, each of the absorber tubes **34** may be coated with a solar absorptive coating. The coating may comprise, for example, a solar spectrally selective surface coating that remains stable under high temperature conditions in ambient air or, for example, a black paint that is stable in air under high-temperature conditions. In some variations, the solar spectrally selective coating is a coating disclosed in U.S. Pat Nos. 6,632,542 or 6,783,653, both of which are incorporated herein by reference in their entirety.

In one variation, receiver structure **5a** has a length of about 12 meters and an overall width of about 1.4 meters. In other variations the length may be, for example, about 10 meters to about 20 meters and the width may be, for example, about 1 meter to about 3 meters.

Referring now to FIGS. **9A-9E**, another example receiver structure **5b** comprises an inverted trough **24** formed, for example, from stainless steel sheeting and having a longitudinal channel portion **26** and side walls **27** similar to those in receiver structure **5a** described above. In receiver structure **5b**, trough **24** is supported and provided with structural integrity by longitudinal members **60a-60c** and arches **62**. Longitudinal members **60a-60c** and arches **62** may be formed, for example, from tube steel and welded together, for example, to form an approximately semi-cylindrical framework **64**. Trough **24** is further supported and provided with structural integrity by transverse bridging members **66** bridging framework **64**. A smooth outer shell **68** of, for example, galvanized steel is attached to framework **64** with, for example, glue. Smooth outer shell **68** provides a low wind profile and sheds water and snow and thus may reduce structural (e.g., strength, rigidity) requirements of receiver structure **5b** and reduce opportunities for moisture to enter the receiver.

The void between trough **24** and outer shell **68** may be filled with a thermal insulating material **32**, which may be the

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same or similar materials as described above with respect to receiver structure **5a** and which provide the functions there described.

A longitudinally extending window **25** is supported by slot **70** and ledge **72** to interconnect the side walls **27** of trough **24** and form a closed, heat retaining cavity **33** within the trough. Window **25** may be formed from glass, for example. Slot **70** and ledge **72** define the transverse width of the aperture through which solar radiation incident from the reflectors of an LFR array may enter trough **24**.

Dust that enters cavity **33** with unfiltered inflowing air might settle on window **25** and reduce its transparency to solar radiation. To reduce this risk, in some variations a gasket material, such as a fiber glass rope, for example is placed between slot **70** and window **25** and between ledge **72** and window **25** to improve the window seal and thereby reduce influx of air and dust into the trough around edges of the window. Alternatively or in addition, an optional laminar flow air tube **74** may provide a laminar flow of air across the inside of window **25** to keep it free of dust without creating significant convective air currents in cavity **33** that might increase loss of heat from cavity **33**. Also, vents may be provided in outer shell **66** or in end caps (not shown) of receiver structure **5b** to provide a relatively low resistance air flow path from outside of receiver structure **5b** to cavity **33** through a material (e.g., insulating material **32**) that filters dust from air flowing into cavity **33**. Such a low resistance path may suppress flow of unfiltered air through other openings into cavity **33**.

Referring now particularly to FIGS. **9C** and **9E**, window **25** may comprise a plurality of transparent (e.g., glass) panes **25a** positioned in an overlapping manner the length of receiver structure **5b**. This arrangement provides a relatively effective seal to influx of air while also providing for thermal expansion of the panes. Overlapping panes **25a** may be clamped together at their overlapping portions by clamps (not shown) applied at their outer edges, for example. Alternatively or in addition, window **25** may comprise a plurality of plates that are positioned in an overlapping manner in the transverse direction (i.e., perpendicular to the long axis of the receiver).

Similarly to receiver structure **5a**, longitudinally extending absorber tubes **34** are provided for carrying a working or heat exchange fluid to be heated by absorbed solar radiation. Absorber tubes **34** may be freely supported in trough **24** by a rolling support tube **35** to accommodate expansion of the absorber tubes during use. Other arrangements for supporting the absorber tubes may also be used. The diameter of the absorber tubes and the ratio of their diameter to the trough aperture may be, for example, as described above with respect receiver structure **5a**. Absorber tubes **34** may be coated with solar spectrally selective coatings as described above, for example.

Two or more receiver structures **5b** may be aligned and coupled end to end using, for example, flanges **76** to form an extended receiver structure **5** which is then utilized as described above. Gaskets may be provided between the joined receiver structures **5b** to reduce influx of air and associated dust at the joint. In some variations, receiver structures **5b** (or **5a**) are joined into groups of (e.g., 3) receiver structures, and the groups are then joined to each other to form an extended receiver **5** using flexible couplings between absorber tubes in adjacent groups. Such an arrangement may accommodate thermal expansion of the absorber tubes during use.

Referring again to FIG. **9D** as well as to FIG. **9F**, the aperture of trough **24** is defined by slot **70** and ledge **72** as noted above. In the illustrated variation, the aperture so defined is located off center with respect to the trough in the

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direction of the polar reflector field and thereby accommodates an LFR array configuration in which the polar reflector field extends further from the receiver than does the equatorial reflector field. In such variations, the receiver and the reflector fields are typically arranged so that a ray reflected by the outer edge of the equatorial reflector row **12E<sub>N</sub>** farthest from the receiver is incident at the largest angle  $\alpha_E$  by which it may be incident on the absorber tube nearest to reflector row **12E<sub>N</sub>**, and so that a ray reflected by the outer edge of the polar reflector row **12P<sub>M</sub>** farthest from the receiver is incident at the largest angle  $\alpha_P$  by which it may be incident on the absorber tube nearest to reflector row **12P<sub>M</sub>**.

The asymmetric aperture illustrated in FIGS. **9D** and **9F** may also provide the advantage of allowing window **25** (e.g., panes **25a**) to be loaded into receiver structure **5b** by inserting window **25** from the polar side through the aperture.

Referring now to FIG. **10**, it may be advantageous to provide spaces (e.g., spaces **A<sub>1</sub>-A<sub>3</sub>**) between absorber tubes **34** in a receiver structure (e.g., receiver structure **5a**, **5b**) to accommodate thermal expansion and movement of the absorber tubes. Such spaces may allow solar radiation reflected from an LFR array to the absorber tubes to pass between the absorber tubes and hence reduce solar radiation collection efficiency, however. In some variations, the absorber tubes are spaced apart without reducing collection efficiency by setting the spaces between absorber tubes so that solar rays reflected from the closest edge of the reflector row closest to the receiver (e.g., from the inner edge of mirror **12P1**) are tangent to adjacent absorber tubes. If the closest reflector row on each side of the receiver is positioned the same distance from the receiver, this method will result in spaces between absorber tubes that vary, with spaces between outer absorber tubes smaller than those between inner absorber tubes. The spacing of the absorber tubes may be simplified by using a uniform spacing equal to the smallest such space determined by this method for all pairs of absorber tubes.

Referring again to FIGS. **8A** and **9D**, for example, in some variations window **25** of receiver structure **5a** or **5b** is coated with an anti-reflection coating to reduce losses due to reflection of incident solar radiation by the window. Anti-reflection coatings are generally selected to optimize transmission of light incident at angles around a particular angle of incidence. In some variations, the angle of incidence at which the anti-reflective coating on window **25** is optimized is selected to maximize the annualized solar energy collector efficiency of the LFR array of which the receiver structure is a part. Such selection may be done using, for example, a ray tracing model of the LFR array.

In some variations fluid flow through absorber tubes **34** in reflector structure **5a** or **5b** may be in parallel unidirectional streams. Other flow arrangements may also be used, however. FIG. **11A** of the drawings shows diagrammatically one example flow control arrangement for controlling flow of heat exchange fluid into and through four in-line receiver structures **15a** of a receiver. As illustrated, each of the fluid lines **34A, B, C** and **D** is representative of four of the absorber tubes **34** as shown in the previous figures.

Under the controlled condition illustrated in FIG. **11A**, in-flowing heat exchange fluid is first directed along forward line **34A**, along return line **34B**, along forward line **34C** and finally along and from return line **34D**. This results in fluid at a lower temperature being directed through tubes that are located along the margins of the inverted trough and a consequential emission reduction when radiation is concentrated over the central region of the inverted trough. A control device **39** may be provided to enable selective control over the channelling of the heat exchange fluid in some variations.

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Alternative fluid flow conditions may be established to meet load demands and/or prevailing ambient conditions, and provision may effectively be made for a variable aperture receiver structure by closing selected ones of the absorber tubes. Thus, variation of the effective absorption aperture of each receiver structure and, hence, of a complete receiver may be achieved by controlling the channelling of the heat exchange fluid in the alternative manners shown in FIGS. 11B to 11D.

FIG. 11E shows an example fluid flow arrangement through a receiver 5 in which 10 parallel absorber tubes 34 are in fluidic communication at one end of the receiver through a header 82. In this example, cold heat exchange or working fluid flows into the receiver through outer absorber tubes 34E and 34P to header 82, and is then distributed by header 82 between inner absorber tubes 34G-34N along which it flows in a return path back down receiver 5 to exit at a higher temperature. As in FIG. 11A, this configuration can reduce thermal loss due to radiation from the absorber tubes. In addition, this down-and-back configuration allows thermal expansion of the absorber tubes to be accommodated at the header end by, for example, allowing the header to move with the absorber tubes as they change in length with changes in temperature.

## Reflectors

The reflectors 12a and 12b described in this section may, in some variations, be suitable for use in the east-west LFR solar arrays disclosed herein, in east-west and /or north-south LFR solar arrays known to one of ordinary skill in the art, and/or in east-west or north-south solar arrays later developed.

Referring to FIG. 12, in some variations a reflector 12a comprises a carrier structure 40 to which a reflector element 41 is mounted. The carrier structure itself comprises an elongated panel-like platform 42 which is supported by a skeletal frame structure 43. The frame structure includes two hoop-like end members 44.

The members 44 are cantered on and extend about an axis of rotation that is approximately coincident with a central, longitudinally-extending axis of the reflector element 41. The axis of rotation does not need to be exactly coincident with the longitudinal axis of the reflector element but the two axes desirably are at least adjacent one another.

In terms of overall dimensions of the reflector, the platform 42 is, for example, about 10 to about 20 meters long and the end members 14 are approximately two meters in diameter. In some variations the platform 42 is about 12 meters long. In some other variations the platform 42 is about 16 meters long.

The platform 42 comprises a corrugated metal panel and the reflector element 41 is supported upon the crests of the corrugations. The corrugations extend parallel to the direction of the longitudinal axis of the reflector element 41, and the platform 42 is carried by, for example, six transverse frame members 45 of the skeletal frame structure 43. End ones of the transverse frame members 45 effectively comprise diametral members of the hoop-like end members 44.

The transverse frame members 45 comprise rectangular hollow section steel members and each of them is formed with a curve so that, when the platform 42 is secured to the frame members 45, the platform is caused to curve concavely (as viewed from above in FIG. 12) in a direction orthogonal to the longitudinal axis of the reflector element 41. The same curvature is imparted to the reflector element 41 when it is secured to the platform 42. The radius of curvature of the transverse frame members 45 is, for example, about twenty to about fifty meters.

The skeletal frame 43 of the carrier structure 40 also comprises a rectangular hollow section steel spine member 46

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which interconnects the end members 44, and a space frame which is fabricated from tubular steel struts 47 connects opposite end regions of each of the transverse frame members 45 to the spine member 46. This skeletal frame arrangement, together with the corrugated structure of the platform 42 provides the composite carrier structure 41 with a high degree of torsional stiffness.

Referring now to FIG. 13, in another variation a reflector 12b has a structure substantially similar to that of reflector 12a, but includes in addition a radial spoke 84 located within a hoop-like end member 44. Spoke 84 is attached to and runs between the hoop-like end member and an end one of the transverse frame members 45, and is also attached to one end of spine 46.

The hoop-like end members 44 of reflectors 12a, 12b are formed from channel section steel, for example, such that each end member is provided with a U-shaped circumferential portion and, as shown in FIG. 14, each of the members 44 is supported for rotation on a mounting arrangement that comprises two spaced-apart rollers 48. The rollers 48 are positioned to track within the channel section of the respective end members 44, and the rollers 48 provide for turning (i.e., rotation) of the carrier structure 40 about the axis of rotation that is approximately coincident with the longitudinal axis of the reflector element 41.

As also shown in FIG. 8, a hold-down roller 48a is located adjacent the support rollers 48 and is positioned within the associated end member 44 to prevent lifting of the reflector under adverse weather conditions.

A drive system, one variation of which is shown in FIG. 15, is provided for imparting drive to the carrier structure 40 and, hence, to the reflector element 41. The drive system comprises, for example, an electric motor 49 having an output shaft coupled to a sprocket 50 by way of reduction gearing 51. The sprocket 50 meshes with a link chain 52 through which drive is directed to the carrier structure 40. The link chain 52 extends around and is fixed to the periphery of the outer wall 53 of the channel-section of one of the end member 44. That is, the link chain 52 affixed to the end member effectively forms a type of gear wheel with which the sprocket 50 engages.

In another variation, a drive chain has its ends fixed to end member 44 at locations adjacent to each other within the channel section of the end member. The remaining portion of the chain forms a loop running around a portion of end member 44 through the channel structure and thence to and around a sprocket such as sprocket 50 shown in FIG. 15. The sprocket is driven bidirectionally by an electric motor through suitable reduction gearing. This arrangement allows for approximately 270° bidirectional rotation of the reflector, and consequently facilitates solar tracking of reflectors in an east-west LFR array.

Referring again to FIGS. 12 and 13, the reflector element 41 is formed, for example, by butting together a plurality of glass mirrors 41a. A silicone sealant may be employed to seal gaps around and between the mirrors and to minimize the possibility for atmospheric damage to the rear silvered faces of the mirrors. The mirrors may be secured to the crests of the platform 12 by a urethane adhesive, for example. In some variations, the mirrors have a thickness of 0.003 m and, thus, they may readily be curved in situ to match the curvature of the supporting platform 42.

Depending upon requirements, two or more of the above described reflectors may be positioned linearly in a row and be connected one to another by way of hoop-like end members 44. In such an arrangement a single drive system may be employed for imparting drive to multiple reflectors.

This disclosure is illustrative and not limiting. Further modifications will be apparent to one skilled in the art in light of this disclosure and are intended to fall within the scope of the appended claims. All publications and patent applications cited in the specification are incorporated herein by reference in their entirety as if each individual publication or patent application were specifically and individually put forth herein.

We claim:

1. A solar energy collector system comprising:  
 an elevated linear receiver extending generally in an east-west direction;  
 a polar reflector field located on the polar side of the receiver; and  
 an equatorial reflector field located on the equatorial side of the receiver;  
 wherein each reflector field comprises reflectors positioned in one or more parallel side-by-side rows which extend generally in the east-west direction, the reflectors in each field are arranged to reflect incident solar radiation to the receiver during diurnal east-west motion of the sun and pivotally driven to maintain reflection of the incident solar radiation to the receiver during cyclic diurnal north-south motion of the sun, and the polar reflector field comprises more reflector rows than the equatorial reflector field.

2. The solar energy collector system of claim 1, wherein the receiver comprises a photovoltaic device which absorbs solar radiation reflected to it by the reflectors and converts the solar radiation to electricity.

3. The solar energy collector system of claim 1, wherein the receiver comprises an absorber that absorbs solar radiation reflected to it by the reflectors to heat a working or heat exchange fluid.

4. The solar energy collector system of claim 1, wherein reflector rows on opposite sides of the receiver are spaced asymmetrically.

5. The solar energy collector system of claim 4, wherein the receiver comprises an absorber that absorbs solar radiation reflected to it by the reflectors to heat a working or heat exchange fluid.

6. The solar energy collector system of claim 5, wherein the receiver is tilted in the direction of the polar reflector field.

7. The solar energy collector system of claim 5, wherein one or more outer rows of the equatorial reflector field have focal lengths greater than their respective distances to a solar radiation absorber in the receiver.

8. The solar energy collector system of claim 5, wherein the receiver comprises a window through which solar radiation reflected by the reflectors is directed to the absorber and the window comprises an anti-reflection coating having a maximum transmission of solar radiation at an angle of incidence that maximizes an annualized solar radiation collection efficiency of the solar energy collector system.

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